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Foreword.

This report consists of three papers. The data used are mainly surface wave recordings from the VLP-station in Kongsberg, Norway. This station is one of the 10 broad band high gain installations presently in operation throughout the World.

PART I

PHASE REVERSAL AND TIME DELAY OF EXPLOSION-GENERATED SURFACE WAVES.

EIVIND RYGG

ABSTRACT

A phase shift of 180° has been found between the Rayleigh wave trains of two closely located Eastern Kazakh explosions The Rayleigh waves from one of the explosions were delayed by about 4 sec relative to the Rayleigh waves from the other explosion. The event generating the delayed Rayleigh waves excited relatively strong Love waves, but these waves were not delayed. Various causes for the anomalies have been discussed - explosion-collapse pairs - depth differences and spallation. It seems that the Love waves of the anomalous event have been generated very near the source at the time of the detonation while the Rayleigh waves have been generated by a secondary event, - collapse- or by spall closure above the explosion.

INTRODUCTION

A 180° phase reversal for Rayleigh waves from explosion-collapse pairs has been well documented in literature (Brune and Pomeroy 1963, Toksøz & al. 1964, von Seggern 1973). Brune and Pomeroy (1963) found from studies of explosions in tuff and alluvium approximately the same initial phase (π) for Rayleigh waves at all azimuths, corresponding to an upward step function in time. Analysis of surface waves from an underground explosion in granite gave a radiation pattern like those expected for earthquakes. The same authors found that the collapses following an underground explosion generated weaker Love waves relative to the Rayleigh waves than the explosions. They concluded that the conversion of Rayleigh waves during transmission could not be the major cause of Love waves, but that these waves must be generated at - or very near the source, possibly by a triggering action of the explosion.

Their findings have been corroborated by other authors (Aki & al. 1969, Aki and Tsai 1972) who also have given new evidences for the same conclusion. In their paper on Love wave generation by explosive sources (Aki and Tsai 1972) found that for large explosions the relative excitation of Love waves did not decrease with depth, contrasting to what had been found for smaller explosions (Kisslinger & al. 1961) Repetition of large shots in the same area gave decreasing Love wave radiation, again contrasting to what had been found for smaller shots.

Viecelli (1973) showed that ground spalling over nuclear explosions could be responsible for most of the Rayleigh wave energy observed for some of the events. If this were the case one would expect a phase reversal of the

Rayleigh waves relative to the elastic case and in addition a small time delay of the Rayleigh waves, depending on the time delay of the spall closure relative to the explosion. In a study of Amchitka explosions von Seggern (1973) reported a small delay (1-2 sec.) of Rayleigh waves from one of the events, and he suggested on the background of Viecelli's calculations that spalling could explain the discrepancy.

In the present paper we shall present evidence that:

i) The Rayleigh waves from two closely located Eastern Kazakh underground explosions of body wave magnitudes 6.0 and 6.1 respectively, are reversed in polarity relative to each other.

ii) The Rayleigh waves from one of the explosions are delayed by about 4 sec relative to the Rayleigh waves from the other explosion.

iii) The excitation of Love waves is much stronger for the explosion with delayed Rayleigh waves.

iv) The Love waves are not delayed and they are not amplitude reversed.

These findings will be demonstrated and discussed with reference to theoretical investigations (Lamb 1904, Lapwood 1949, Harkrider 1964, Alterman and Aboudi 1969) model experiments (Gupta and Kisslinger 1964) and recent papers on surface wave generation from explosions (Rodean 1971, Aki and Tsai 1972, Von Seggern, 1973, Viecelli 1973).

THE DATA

The events to be discussed in this paper are the Eastern Kazakh presumed underground explosions given in Table I. The origin times and epicenter coordinates have been taken from the ISC bulletins.

TABLE I

Year	Date	Or.time	Lat	Long	mb
1972	10 Dec	04:26:57.8	49.80N	78.10E	5.6
"	"	04:27:07.6	49.97N	78.95E	6.0
1973	23 July	01:22:57.7	49.94N	78.85E	6.1

The recordings which have been used have been taken from the NORSAR array and the VLP-stations in Kongsberg, Norway (KON) and Chiang May, Thailand (CHG). Figure 1 shows the locations of the VLP stations and the great circle paths to the test site area in Eastern Kazakh. The figure also show a detailed map of the locations of the three explosions. Figure 2 shows the instrument responses of the long period systems at Kongsberg VLP and NORSAR, and a comparison of typical surface wave recordings at these two stations.

Rayleigh waves

On 10 Dec. 1972 two events are reported with body wave magnitudes 5.6 and 6.0. According to the ISC solutions the smallest of these events was detonated 9.8 sec before the other, and at a location which gave some 33 km shorter great circle path to Kongsberg. The surface waves from this explosion should therefore arrive at Kongsberg about 20 sec before the surface waves from the largest explosion.

However, in our experience (Bruland and Rygg 1975) one would not expect visible surface wave recordings at Kongsberg from Eastern Kazakh explosions of this magnitude under normal noise conditions. We shall return to this point later and justify that we in the following presentation assume that the smallest explosion is responsible for a very small or negligible part of the surface waves recorded on 10 Dec. 1972.

According to the solutions given by the ISC the seismic wave trains from the 10 Dec. 1972 explosion and the 23 July 1973 explosion should be in phase and in the same position at 04:43:10 and at 01:39:00 respectively, if the source mechanisms and the propagation paths were identical. In figure 3 the actual Kongsberg ZHI-recordings have been put on top of each other so that these points of time coincide. We notice that the Rayleigh wave trains are approximately 180° out of phase. After reversing the polarity of the 10 Dec 1972 recording and giving it a small time advance ($\sim$ 4 sec) the match between the traces is almost perfect throughout the wavetrains. This indicates that:

i) Both recordings represent single events.

ii) The Rayleigh wave trains are polarity reversed relative to each other, and the wave train of 10 Dec 1972 is delayed.

The same conclusion can be drawn from Figure 4 where we have computed the cross-correlation between the ZHI-recordings and the associated phase spectrum difference. The form of the crosscorrelation function resembles a polarity reversed autocorrelation function. The peak value is negative and it is located at a lag of 14 sec. Since the recordings used start at 01 39 00 and 04 43 00 and these signals were supposed to be in phase at 01 39 00 and 04 43 10 respectively, this means:

i) The Rayleigh waves of the event 10 Dec 1972 04:27:07.6 are delayed about 4 sec relative to the Rayleigh waves of the event 23 July 1973.

ii) The delayed Rayleigh wave train is 180° out of phase relative to the Rayleigh wave train without delay.

The comparison of traces in the time domain provides an average measure of the similarity, i.e.: At any distant of time we are comparing the sum of Fourier components with different amplitudes and phase angles. On top of Figure 4 is shown the phase angle difference for each Fourier component, and as we see, the phase difference is very close to π throughout the frequency band. (The linear phase angle given by the inclined lines on the figure, represents a time shift of 14 sec which is the time lag of the crosscorrelation peak value).

The same conclusions can also be drawn from comparison of the energy distribution in the time domain. Figure 5 shows the energy periods as a function of time for the two Kongsberg ZHI-recordings when they are in the positions shown on the figure. (The 10 Dec 1972 recording has been polarity reversed and time advanced about 4 sec.) A moving window technique was used to prepare this figure: The energy density within a moving window was computed as a function of time for different periods. The window used was linearly tapered (Fejer weights) and had a length of four times the period to be analysed. The energy curves thus computed were normalized relative to the maximum energy for each period and plotted as a function of period and time.

The energy distribution throughout the wavetrains is very similar, with nearly the same width and location of the energy curves, indicating that each recording is mainly due to one dispersed Rayleigh wave train from the same area.

We have examined records from the World wide VLP station net. Apart from Kongsberg only one of these stations, CHG in Thailand, gave recordings of the two explosions that could be used in this study. This station is located in nearly the opposite azimuth direction to Kongsberg as seen from the Eastern Kazakh test area. The surface wave trains at CHG were poorly developed compared to the Kongsberg recordings, but the cross-correlation function between the vertical readings also here shows a peak value which is negative (Fig. 6). Again we find that the form of the crosscorrelation function resembles an autocorrelation function. The peak value is located at a lag of 16 sec, corresponding to a relative delay of 6 sec of the Rayleigh waves of the 10 Dec 1972 explosion. Because of the poor signal to noise ratio this lag value must be regarded as uncertain, but we notice that it is of the same order of magnitude as the values found for signals with better signal to noise ratio (Kongsberg and NORSAR).

We do not present correlation functions of the NORSAR recordings and for the following reasons: The SNR gain of a correlation procedure for seismic signals depends on the time duration and bandwidth of the signal to be enhanced. Relative to the HGLP systems the NORSAR LP-instruments are narrow band (Fig.2). Since we are dealing with dispersed wavetrains a narrowband system will also have the effect of shortening the signals, especially in the long period end (Fig.2). Surface wave recordings from Eastern Kazakh events therefore tend to be both narrowband and of short time duration and correlation is not the proper procedure to enhance the signals. Instead we look at the details of the recordings which often are well developed because of good time resolution. Figure 7 shows amplitude normalized NORSAR LPZ-recordings from the same instrument of the Kazakh events 10 Dec 1972 and 23 July 1973. As before the 10 Dec 1972 recording has been reversed and time advanced about 4 sec. The delay of the Rayleigh waves 10 Dec 1972 is well demonstrated, so is also the excellent fit of the details of the wavetrains. Actually, the fit is so good that details of the wavetrains which at a first glance would be classified as seismic noise, must be interpreted as part of the Rayleigh wave train. (The picture is of course even more convincing when all the instruments in the array are used.)

Love Waves.

Because of noisy Kongsberg EHI-recordings we have not rotated the horizontal components to separate the transverse and radial earth movements. However, the great circle wave paths cross Kongsberg and NORSAR at an azimuth of about 73^{o} so the LPNS-instruments record nearly pure Love wave trains (Fig. 8 and 9). In Figure 8 is shown the Kongsberg NHI recordings of the two explosions, and their crosscorrelation function. The recordings are equally scaled so the differences in amplitudes are real. When the Love wave recordings are put on top of each other at the expected times of arrival (not shown on the figure),the fit is good. The cross-correlation function shown on the figure peaks at a lag of 11 sec while the "correct" lag according to the ISC bulletins would be 10 sec. When we used varying lengths of the recordings the correlation function peaked at lags between 8-11 sec. and this has been taken as an indication that the Love wave trains were arriving at Kongsberg without delays relative to each other. This is also confirmed by the NORSAR LPNS-recordings shown on Figure 9, where some of the Love wave recordings from the two explosions have been put on top of each other at the expected times of arrival. Note that on Figure 9 the amplitudes of the Love waves of 10 Dec. 1972 should be multiplied by approximately 3 to get the correct amplitude relations.

From Figure 8 and 9 we conclude:

i) The Love wave trains from the two explosions 10 Dec 1972 and 23 July 1973 indicate identical Love wave radiation phases.

ii) The explosion of 10 Dec 1972 excited relatively much stronger Love waves than the explosion of 23 July 1973.

The Rayleigh Wave recordings of 10. Dec 1972. One or two explosions?

We now return to the question: Do we record surface waves from one or two explosions on 10. Dec 1972? This becomes a problem of analyzing the Rayleigh wave recordings since the Love wave recordings leave no doubt that the Love waves are generated by the largest explosion (Table I and Figs.8 and 9.)

As was mentioned above, the Kongsberg ZHI recording of 10 Dec 1972 (Fig. 3) indicates that the Rayleigh wave train may be a composite signal. The spectra of the ZHI recordings are given in Figure 10 and we notice that there is a hole in the spectrum of the 10 Dec 1972 recording at about 0.045Hz. Now suppose that this recording is composed of a characteristic signal f(t) plus a time advanced - (τ sec) - and polarity reversed version of the signal multiplied by some arbitrary constant c:

$$s(t) = f(t) - cf(t+\tau)$$

The Fourier transform of the composite signal will be:

$$S(\omega) = F(\omega) \left(1-ce^{i\omega\tau}\right)$$

and its spectrum:

$$|S(\omega)|^2 = |F(\omega)|^2 \left(1 + c^2 - 2c\cos\omega\tau\right)$$

Thus the energy spectrum will be modulated by the terms in the paranthesis.

The modulation curve for τ = 25 sec and c = 0.2 has been plotted on Figure 10 and fits reasonably well with the trend of the spectrum. The calculation is of course sensitive to small changes in τ, for example, for τ = 22.5 sec the first minimum in the modulation curve coincides exactly with the hole in the actual spectrum. The choice of 25 sec was based on the differences in origin times and great circle paths and on the documented delay of the Rayleigh waves of the largest explosion. Variations in the magnitude of c will merely alter the amplitude of the modulation curve, but a change of sign in c would result in an interchange of maxima and minima of the modulation curve. It seems most likely therefore, that the ZHI recordings of 10 Dec 1972 represent Rayleigh waves of two explosions, separated in time by 22-25 sec and with a phase difference of 180°. This is supported by the correlation functions of the recordings: In Figure 11 is shown the autocorrelation function of the Kongsberg ZHI recording of 10 Dec 1972. The secondary negative extrema are characteristic for the autocorrelation of a signal composed of signals which are identical in form but whose size, polarity and time onsets are different. These extrema also occur on the auto-correlation function of an additively constructed recording where the 23 July 1973 explosion has been used as a master event.

In Figure 11 we also can compare the ZHI cross-correlation functions of 23 July 1973 - 10 Dec. 1972 and of 23 July 1973 - Recording constructed using 23 July 1973 as a master, and again we find a striking similarity between the real and the similated correlation functions.

In conclusion we can say that it is probable that the wave train we see on the ZHI-component on 10 Dec. 1972 is a composite wave train, but the energy content of the Rayleigh waves from the first (m_b=5.6) explosion is negligible compared to the energy content of the Rayleigh waves from the second(m_b = 6.0) explosion. The Rayleigh wave trains from the two explosions are 180^{o} out of phase and the time difference is 22-25 sec. The Love waves recorded are generated by the largest explosion.

DISCUSSION

The excitation of various modes of surface waves from explosions have been commonly observed, but the mechanism is not well understood (Aki and Tsai 1972).

An excellent review of the theory on explosion generated seismic signals has been given by Rodean (1971).

The polarity differences demonstrated in the previous sections are due to differences in initial phases of the sources. Since the initial direction of motion of the Rayleigh wave signals is controlled by the direction of the applied stress function rather than the actual shape of the function it is not essential here what kind of source function one considers (e.g. impulse type, step type).

In a classic paper Lamb (1904) discussed the surface displacements due to different time functions for a surface line source in a semi-infinite elastic medium.

In a two dimensional nondispersive medium and with an impulse source function of the form

$$Q(t) = \frac{Q}{\pi} \frac{\tau}{t^2+\tau^2} \quad \text{(Q and } \tau \text{ are real, positive constants)}$$

the Rayleigh wave particle motion at a distance from the source is elliptic retrograde with its first motion upward and toward the source (Fig. 12).

In another classic paper Lapwood (1949) studied the disturbance due to a buried line source, and for an impulsive input it can be shown that the initial surface displacement due to the Rayleigh wave is nearly the opposite to the surface source case (Fig. 12). The results shown on Figure 12 were obtained for two dimensional models, but Lamb (1904) also showed that the general form of the surface displacements is the same in the three dimensional case.

Theoretical studies have also been conducted using more realistic earth models. Harkrider (1964) showed that a downward point force in a layered half space generates Rayleigh waves 180° out of phase with contained explosion generated waves. Alterman and Aboudi (1969) computed the pulse shapes from point sources in a layered sphere. (For $\Delta = 45^{\circ}$ the fundamental mode Rayleigh wave has essentially the same first motion and shape as the solution given by Lapwood (1949).

In a model study Gupta and Kisslinger (1964) estimated the depth at which an explosive source in a two dimensional model changed from acting as a downward impulse to acting as a buried source. Using different model material they found that the source depth corresponding to reversal of polarity of Rayleigh waves was equal to the radius of the zone of inelastic failure around the shot.

Fig 13 shows the Rayleigh wave signals obtained in our laboratory by using an impulsive surface source in Plexiglas. The pulse is formed by a piezoelectric ceramic disc with a diameter of 12.7 mm. In a low speed material as Plexiglas (α = 2360 m/s, C_R = 1250 m/s) this is a good approximation to an impulsive input source, but because of the dimensions of the crystal it is not possible to simulate neither point sources nor line sources. With our equipment the nearest we could get to a "buried" source situation was to put the crystal on the edge of the model material. Fig. 14 shows the Rayleigh waves when the pulse-generating crystal was located in this position.

Depth differences

It is evident from the theory and from the experimental results that depth differences could explain the polarity reversal of the Rayleigh waves. According to Gupta and

Kisslinger's experiments, however, this would require that one of the (large) explosions were detonated at a depth equal to or less than the radius of the "equivalent cavity". This radius is dependent of the material around the shot. For weak, dry materials the radius of the inelastic region can go up to 3 times the radius of the gas cavity. For hard materials the ratio may be as much as 5 or 10 (Springer 1974). Detailed geological maps of the area are not at our disposal, but Eastern Kazakh is a post Herzynian platform. In the region of Semi-Palatinsk granite massifs are intruded into the Upper Paleozoic, (Nalvikin 1973).

An explosion with a radius of the gas cavity of the order of 100 m and a corresponding radius of the inelastic volume of around 500 m might have the effect of a downward force if it were detonated at depths $\ll 500$ m. However, such a source would not explain the delay of the Rayleigh waves if these waves were generated directly by the explosion, and not by a secondary source. Neither would it explain the different relative delay properties between Love waves and Rayleigh waves. In fact, the delay found for Rayleigh waves on the one hand and the lack of delay for Love waves on the other hand strongly suggests that the Rayleigh waves of the largest event of 10 Dec 1972 have been generated by a secondary source, while the Love waves in each case were generated at or near the explosions and at the time of detonation.

Differences in elastic radii of the explosions must also be rejected as a possible cause of the travel time differences, and for the following reasons:

a) The explosions are about the same magnitudes, and
b) even if the yields were different the elastic radii scale as the cube root of the yield, so this effect is negligible.

Cavity Collapse

Following an explosion a cavity collapse occur from a few seconds to several days or weeks after the main event. (Houser 1969). von Seggern (1973) demonstrated two P-arrivals from the Milrow collapse - the first associated with the start of the collapse and the second due to the impact of material on the cavity floor. It has also been shown that cavity collapses excite relatively weaker Love waves than do the explosions. (von Seggern 1973).
A cavity collapse would of course explain both the time delay and the polarity reversal reported in this paper. However, the major collapse rarely occurs so close in time after the main event and it is doubtful if a collapse could generate Rayleigh waves of the order of magnitude reported in this paper, without giving rise to a prominent P-arrival.

Spalling

Several authors have considered the possibility of secondary sources formed by surface spallation following an underground nuclear explosion (Eisler and Chilton 1964, Eisler et al. 1966, Viecelli 1973, Springer 1974).

Spallation occurs when a compressive shock from an underground explosion is reflected at the surface. The downward travelling tension pulse and the incident compressive stress wave may at some depth interfere to produce a tensile stress exceeding the sum of the tensile strength of the rock and the lithostatic pressure. This results in separation and upward movement of one or more layers of the Earth, referred to as "spall" layers. The shock occurring when this material falls back to the surface in turn generates seismic energy, and it has been claimed that this secondary source could be responsible for the seismic surface waves observed from explosions. In his paper Viecelli (1973) investigated the possibility of generating Rayleigh waves by spall closure and found that the computed Rayleigh wave amplitudes corresponding to realistic spallation were about 2.7 times larger than the amplitudes computed under elastic conditions.

Springer (1974) estimated the delay of the spall-generated P_s wave following the explosion - generated P waves for several US-explosions, and for large Nevada explosions P_s-P was of the order of magnitude as observed here. ($\sim$ 3 sec).

Clearly, if spallation were responsible for the Rayleigh wave generation one would have two differences compared to the elastic case:

i) The initial phase would be of opposite sign, and
ii) The Rayleigh waves would be delayed by some amount, depending on the depth, size of charge and the material above the shot.

In fact, Viecelli (1973) in order to support the theory suggests looking for anomalous time delays in the surface wave arrivals from explosions.

Von Seggern (1973) reported a delay of 1-2 sec of the Rayleigh Wave train from the Milrow explosion relative to the Longshot explosion on Amchitka Island. Taking the depth differences and the differences in ballistic spall period from accelerometer data into account, it seemed reasonable that most of this delay could be explained by the spall theory of generation (von Seggern 1973, Viecelli 1973).

As we have demonstrated in our case both the phase reversal and the time delay have been found, but both anomalies are connected only to the Rayleigh wave trains. It is therefore possible that on one occasion (10 Dec. 1972) the explosion has been responsible for the generation of the Love waves while the spall closure was responsible for the generation of the Rayleigh waves.

Love waves

The possibility that mode conversion during transmission might be responsible for the Love waves recorded after an underground explosion (Oliver et.al 1960) has been investigated and rejected by several authors (Brune and Pomeroy 1963, Aki 1964, Aki and Tsai 1972). Our data indicate that if the Love waves were generated by secondary effects this has not caused any detectable delay. Therefore, since the Rayleigh waves reported on the same occasion were delayed, the possibility of conversion of Rayleigh waves as a cause of Love wave generation must be rejected in our case.

Aki and Tsai (1972) noted that while Rayleigh wave forms repeated very well for repeated explosions the Love wave amplitudes varied considerably from event to event. The same authors also studied the dependence of Love wave generation on the shot depth and charge size and found that the relative amount of Love wave excitation increased with both these parameters. The decrease of Love wave excitation from shots in the same area was taken an indication that tectonic stress release was the major cause of Love waves from NTS-explosions. By studying only two (or three) explosions we are of course not able to give any conclusive evidence in support of this conclusion, but also in the present case the last explosion from the same area excited the weakest Love waves.

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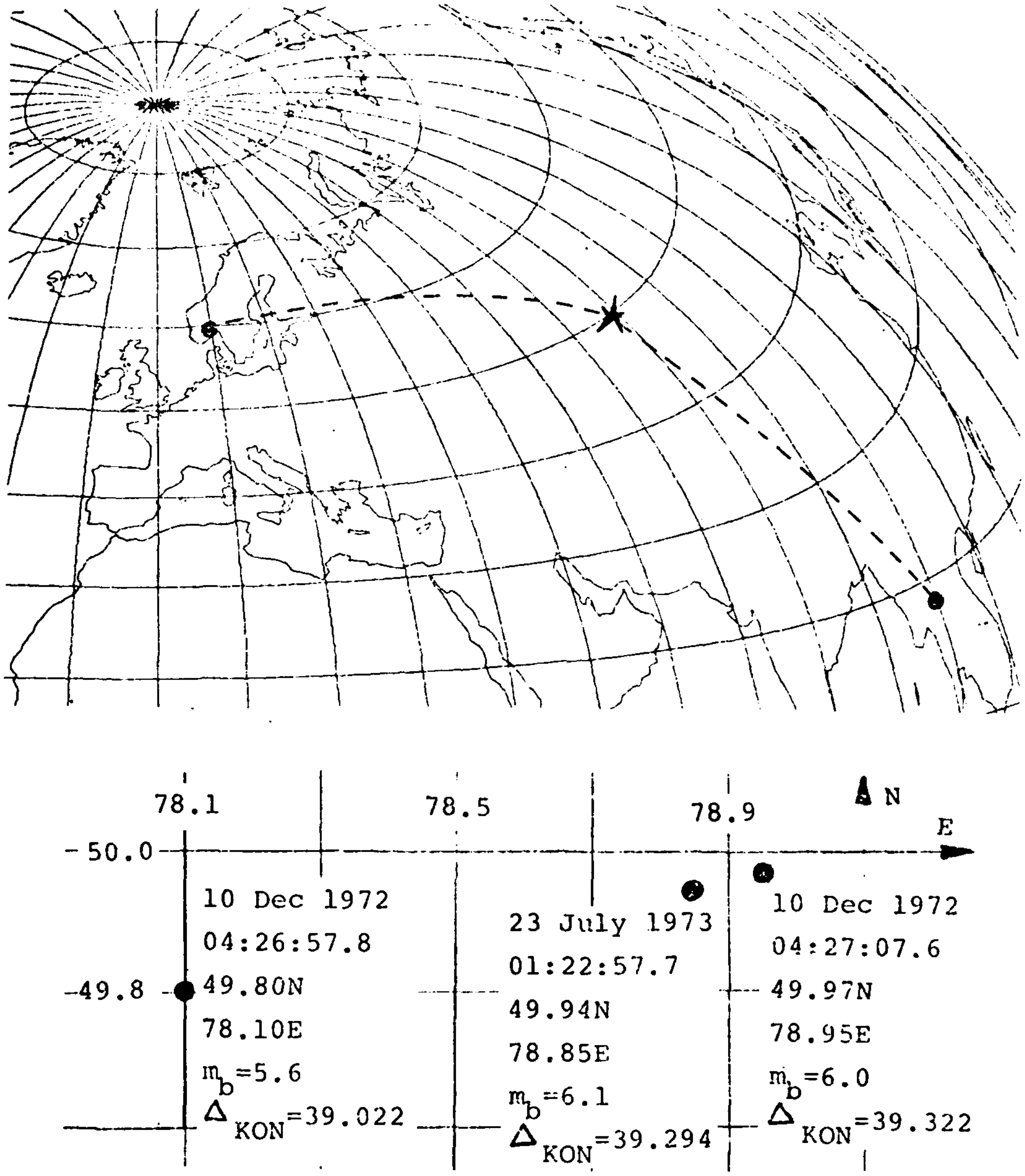


Fig. 1 Approximate great circle paths from the Eastern Kazakh test sites to KON (Norway) and CHG (Thailand). Below the locations and ISC parameters of the three events discussed in the text.

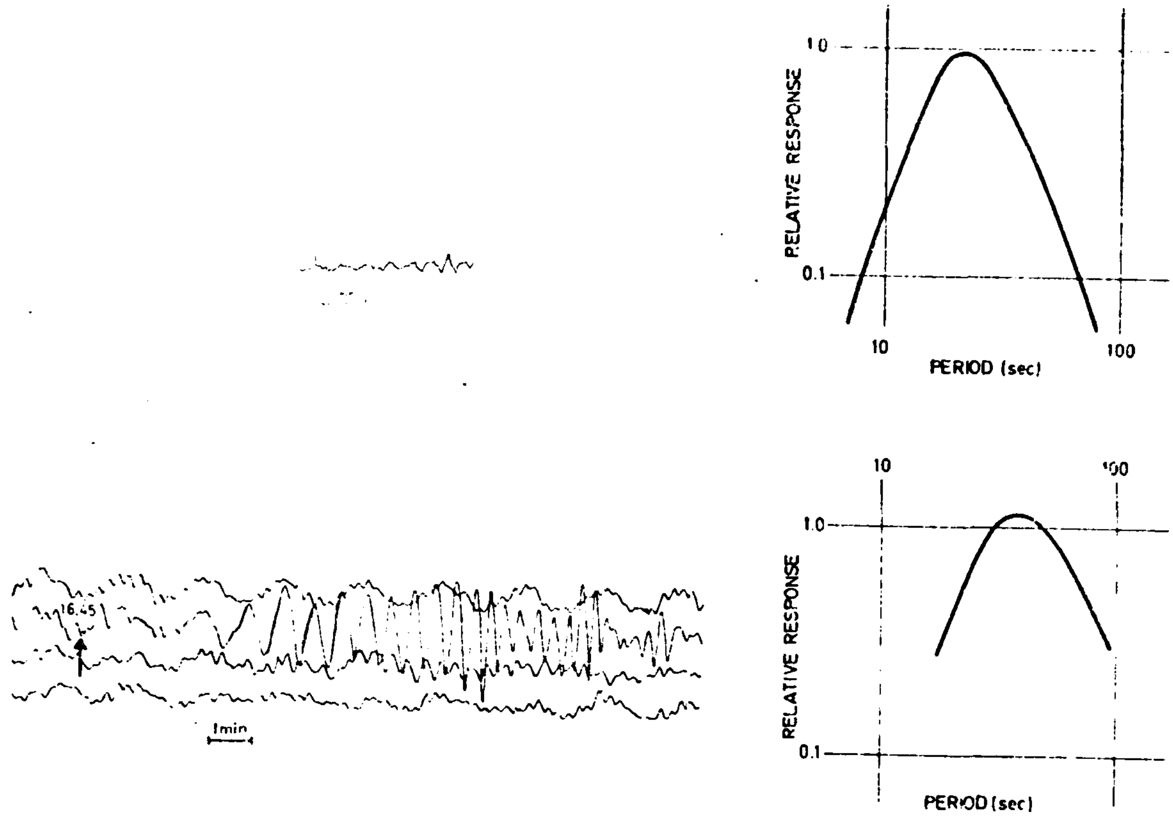


Fig. 2 Top: NORSAR LPZ-recording of an Afghanistan USSR border region event of 01 Oct. 1971. The instrument response to the right.

Below: The Kongsberg ZHI-recording of the same event. The broadband instrument response to the right.

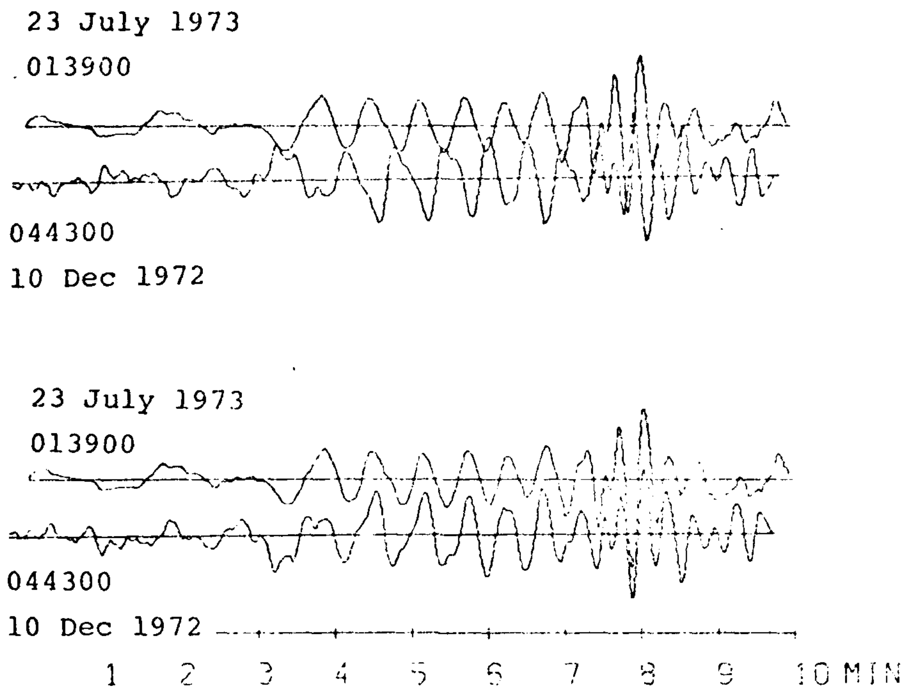


Fig. 3 Top: Kongsberg ZHI recordings of the Kazakh events 23 July 1973 and 10 Dec. 1972. The Rayleigh waves are lined up at the points of time where they should coincide according to the ISC epicentral coordinates and origin times. Below: The same traces with the 10 Dec. 1972 recording polarity reversed and time advanced about 4 sec. The fit throughout the dispersed wavetrains is clearly demonstrated.

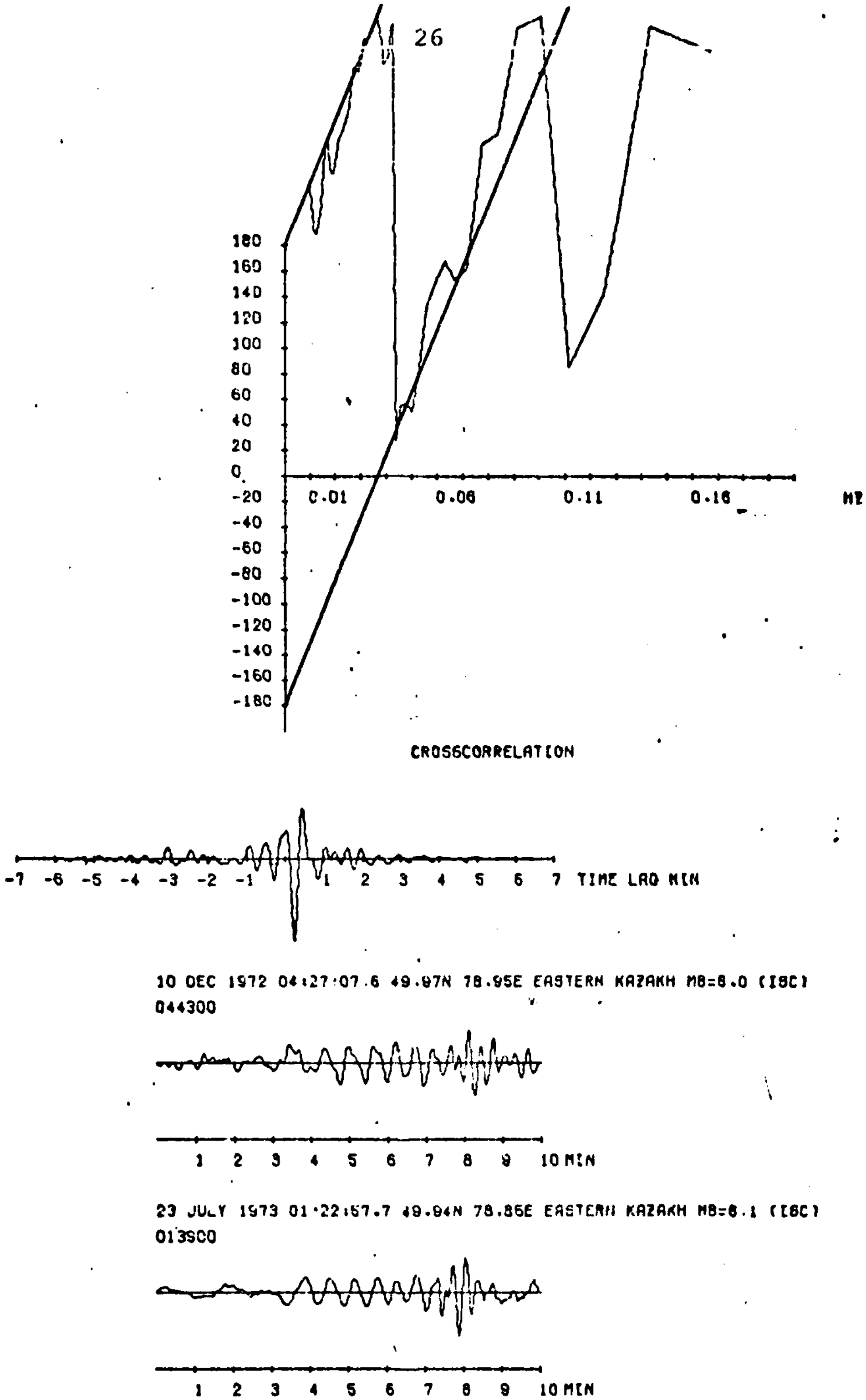


Fig. 4 Kongsberg ZHI recordings, crosscorrelation function and phase angle differences between the 10 Dec. 1972 and the 23 July 1973 event. The linear phase angle given by the solid lines represents a time shift of 14 sec which is the location of the crosscorrelation peak relative to 0-lag.

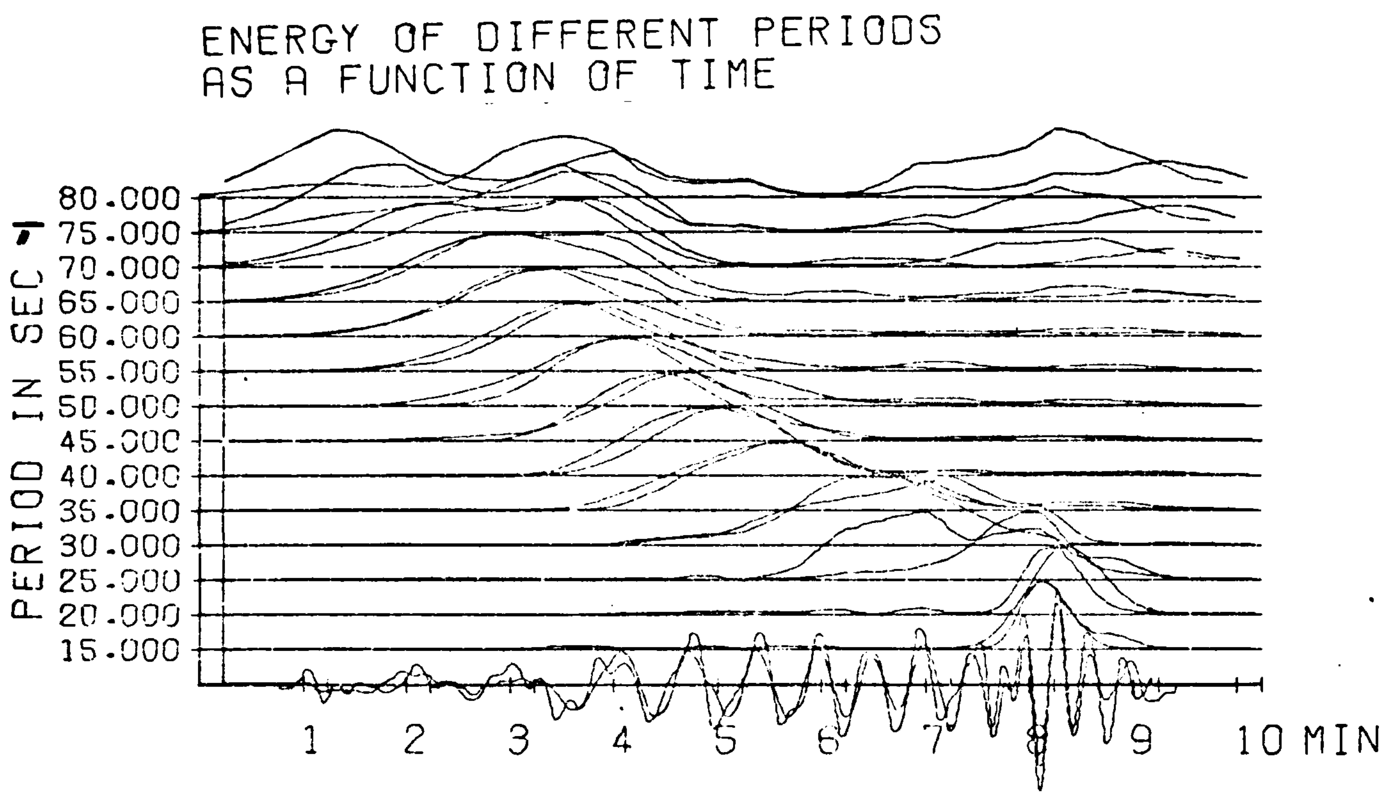


Fig. 5 Energy of different periods as a function of time for the KON ZHI recordings 23 July 1973 and 10 Dec. 1972 (the latter polarity reversed and time advanced 4 sec.)

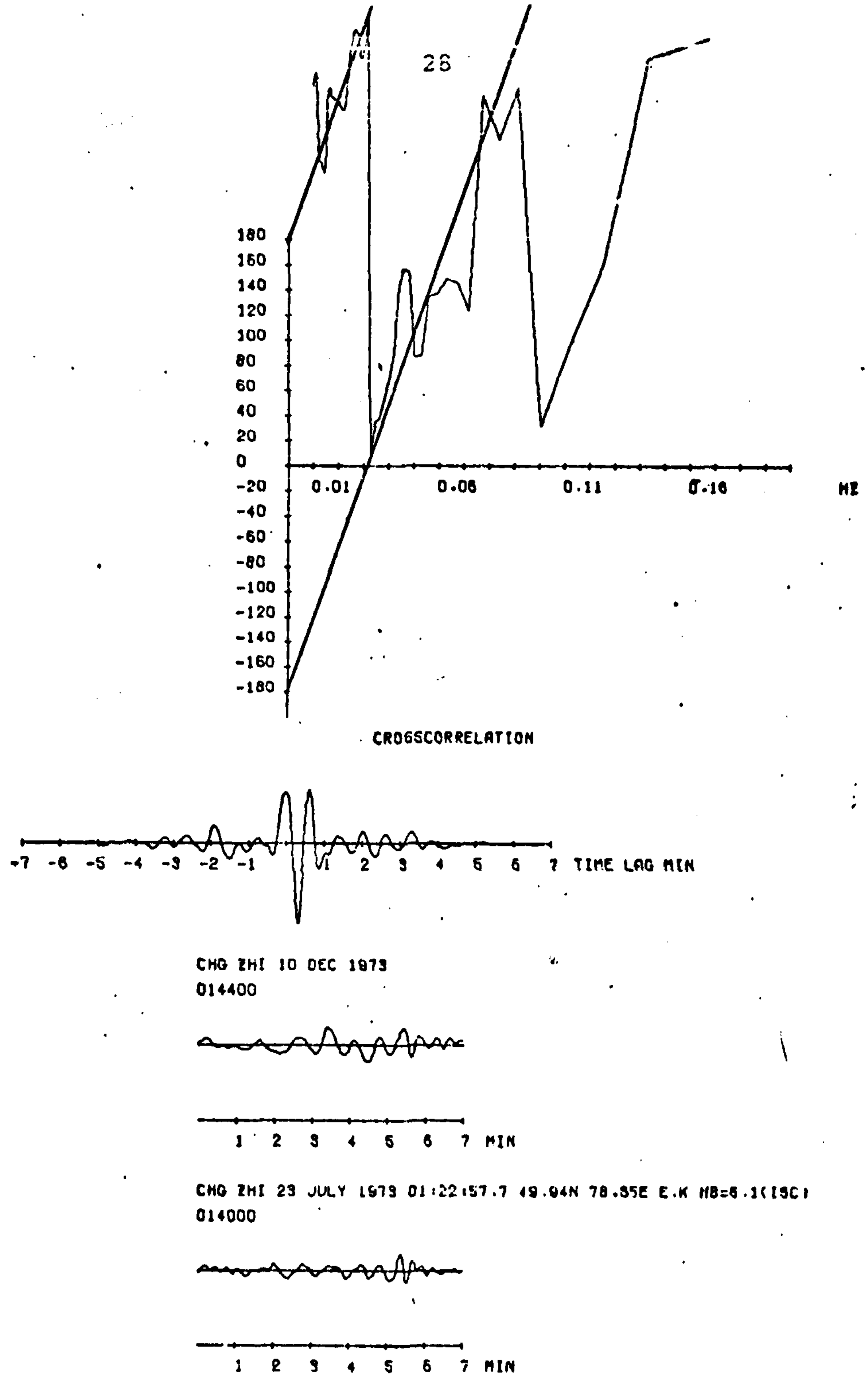


Fig. 6 CHG ZHI recordings, crosscorrelation function and phase angle differences between the 10 Dec.1972 event and the 23 July 1973 event. The linear phase angle given by the solid lines represents a time shift of 16 sec. which is the location of the cross-correlation peak relative to O-lag.

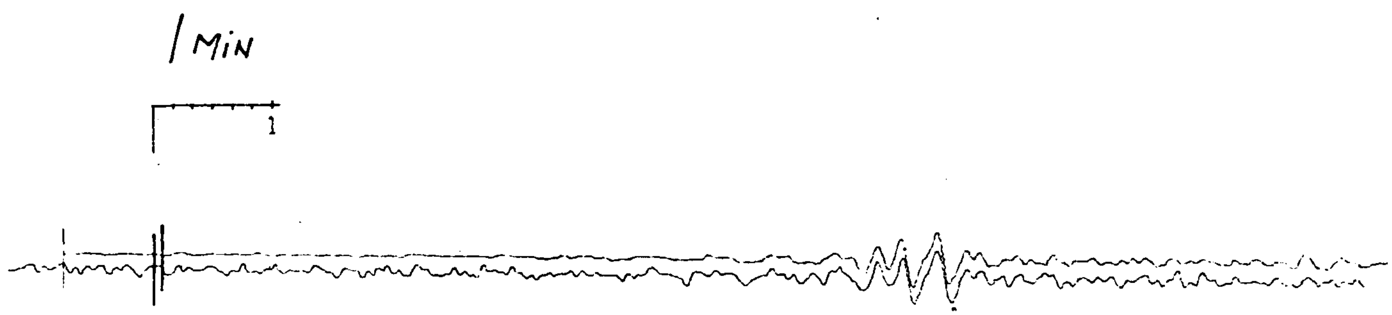


Fig. 7 Sample NORSAR LPZ recording of 23 July 1973 (top) and a polarity reversed recording of 10.Dec. 1972. The two vertical bars represent points of time where the recordings should be in phase according to the origin times. The figure again demonstrates that the Rayleigh waves of the 10 Dec.1972 explosion are delayed by about 4 sec. relative to the Rayleigh waves of the 23 July 1973 explosion. (Time scale on top).
Note that the traces are normalized. To get the correct amplitude relations the July 1973 recording should be multiplied by an amplitude factor of about 1.3.

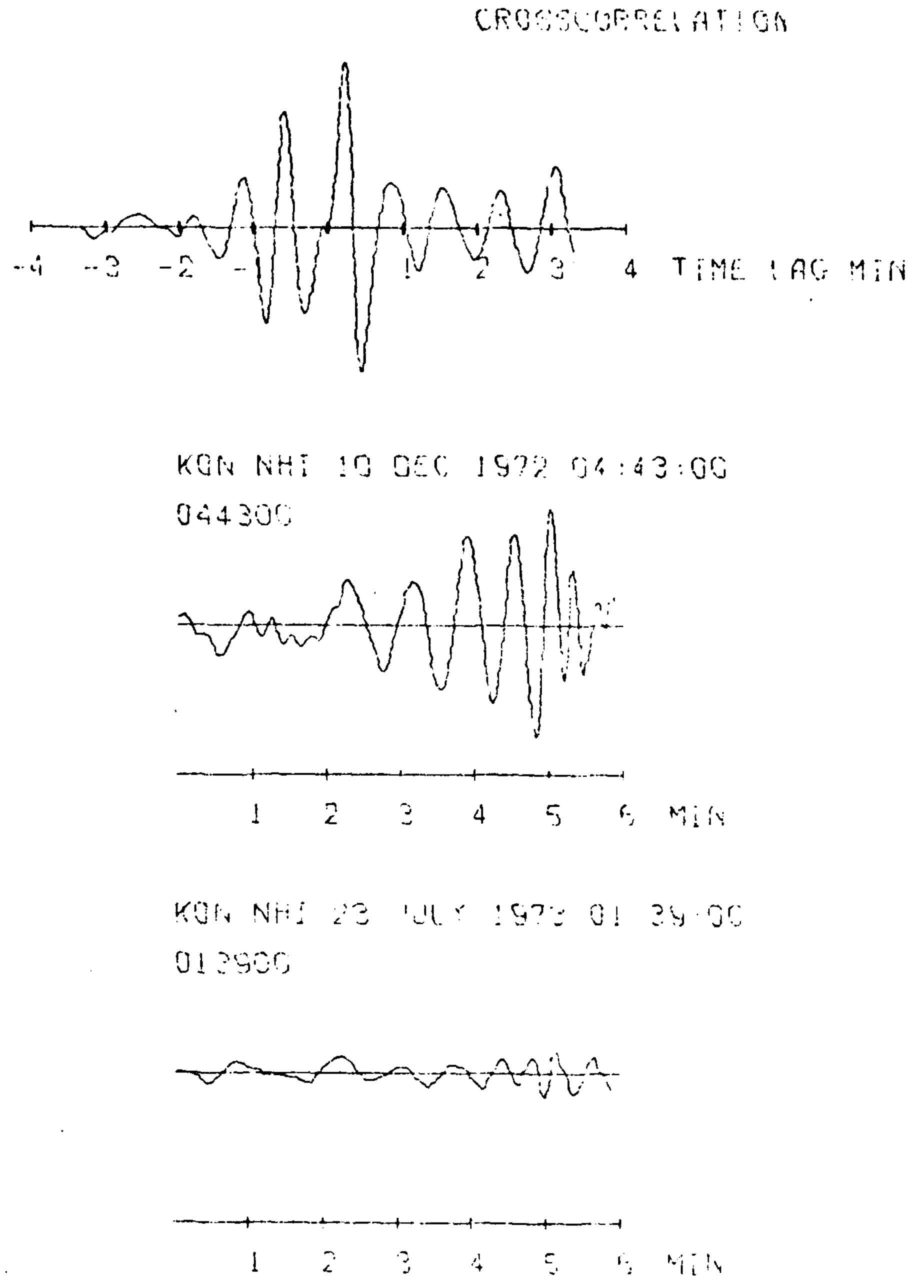


Fig. 8 Kongsberg NHI recordings 10 Dec 1972 and 23 July 1973 and crosscorrelation function. The correlation function peaks at a lag of 11 sek.

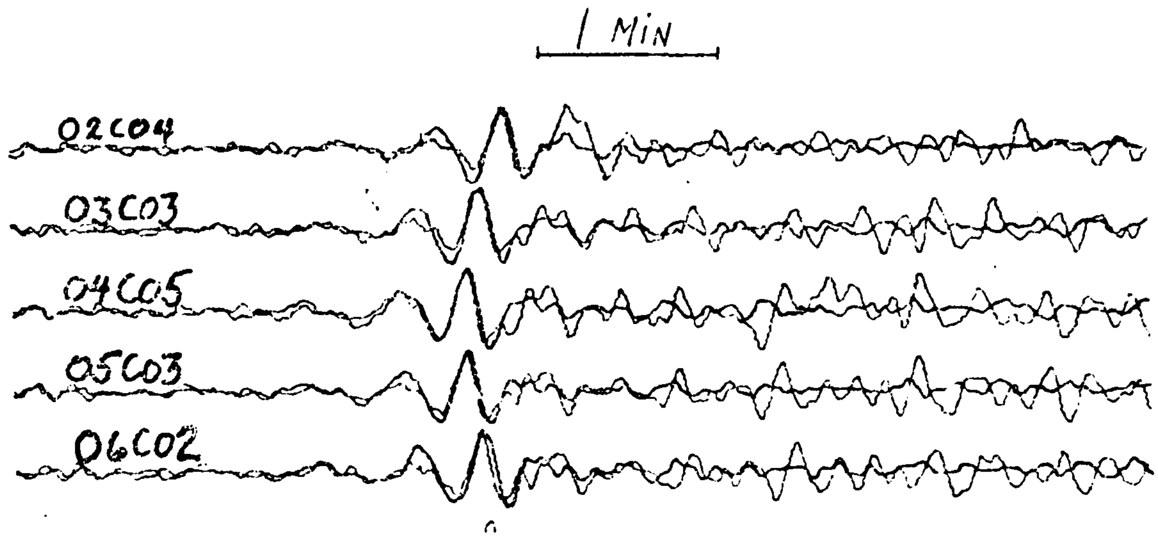


Fig. 9 Some NORSAR LPN-recordings of the Kazakh events from the same instruments put on top of each other. The heaviest lines represent the event of 10 Dec. 1972. We notice that there is a very good fit between the Love wave trains when they are put on top of each other at the expected times of arrivals, contrasting to what was found for the corresponding Rayleigh wave trains. To get the correct amplitude relations the recordings of 10 Dec. 1972 should be multiplied by a factor of about 3.

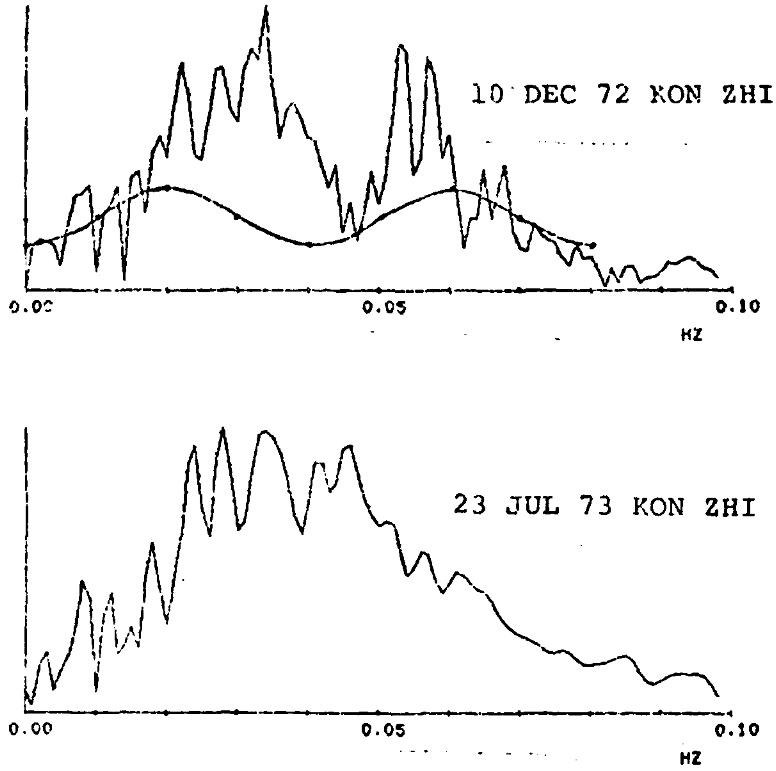


Fig. 10 Normalized energy spectrum of the Kongsberg ZHI recordings of 10 Dec. 1972 (top) and 23 July 1973. On the upper diagram the spectral modulation curve $1 + c^2 - 2c \cos\omega\tau$ has been plotted for c = 0.2 and $\tau = 25$

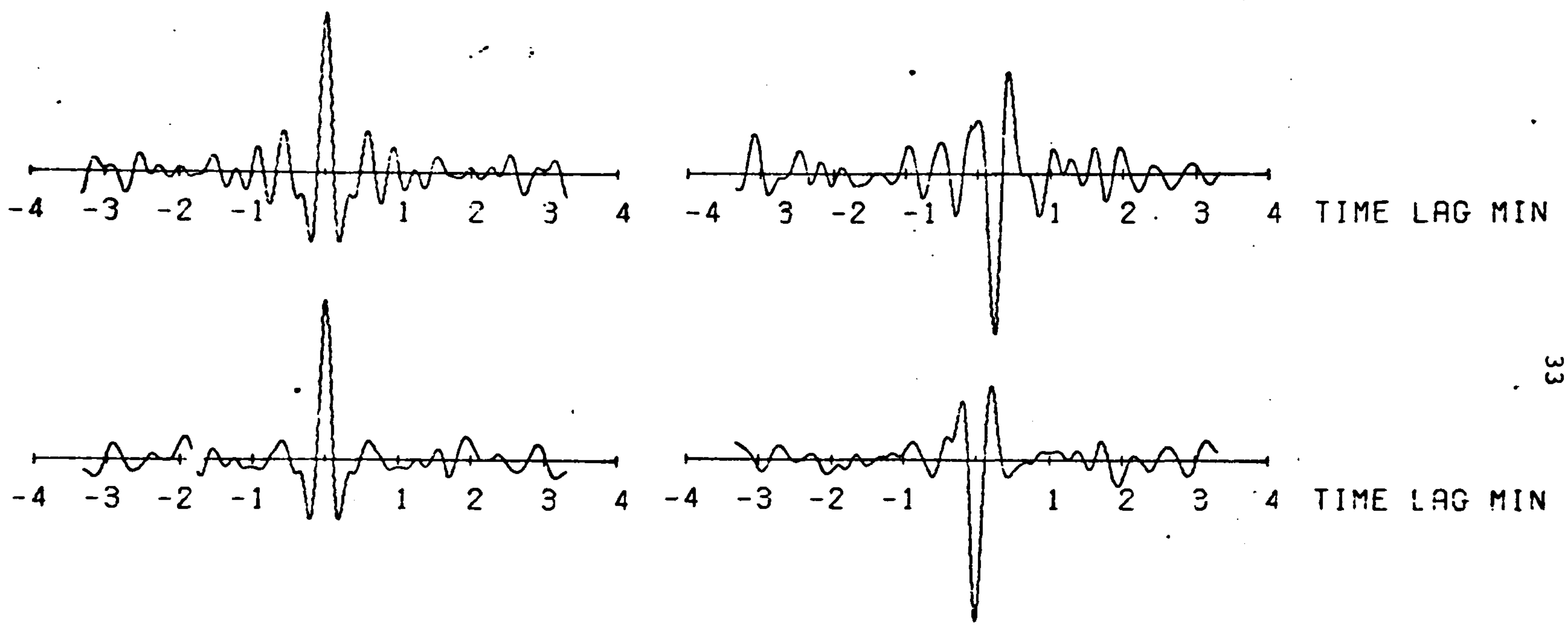


Fig. 11 Top left: Autocorrelation function of Kongsberg ZHI 10 Dec. 1972.
Bottom left: Autocorrelation function of Kongsberg ZHI 23 July 1973 plus a polarity reversed and 25 sec time advanced version of itself x0.2.
Top right: Kongsberg ZHI crosscorrelation function 23 July 1973 - 10 Dec. 1973.
Bottom right: Crosscorrelation function between the Kongsberg ZHI 23 July 1973 recording and the same recording polarity reversed plus a 25 sec time advanced version of the original recording x0.2.

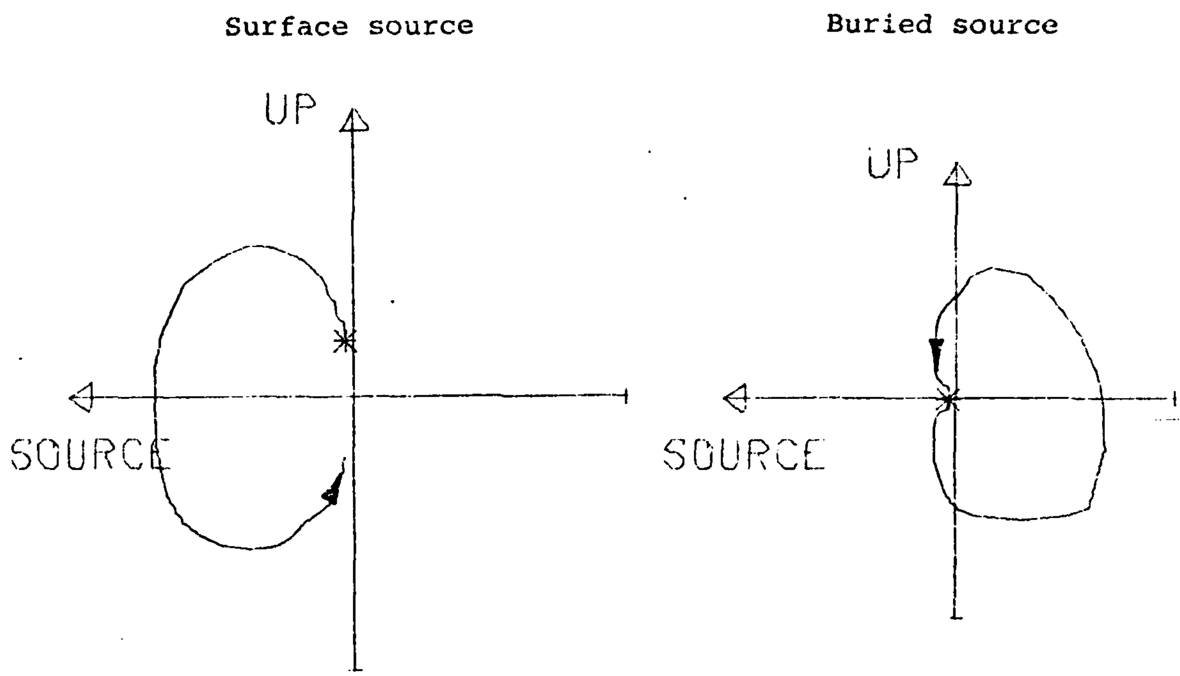


Fig. 12 Rayleigh wave particle motion plot for an impulsive surface line source. (Lamb 1904) and for a buried source (Lapwood 1949). The plots have been constructed by digitizing the horizontal and vertical components, and the irregular forms are due to digitizing errors.

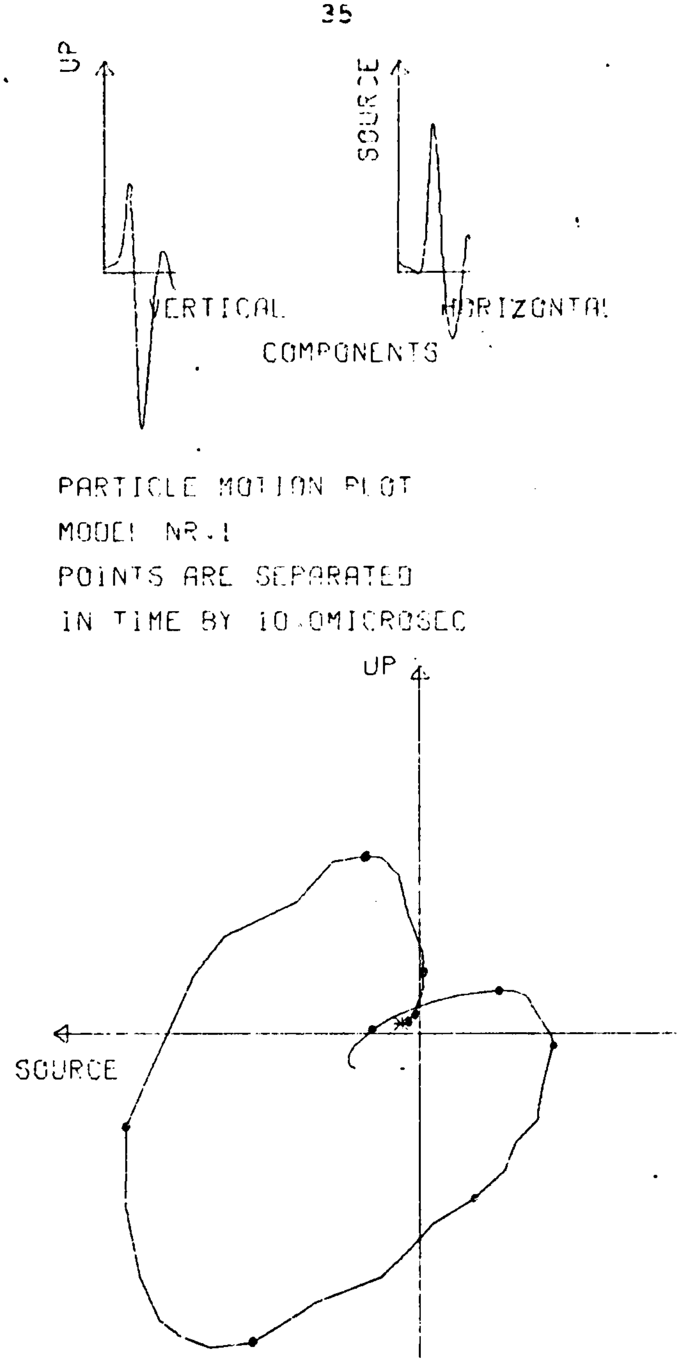


Fig. 13 Experimental Rayleigh wave signals (top) and particle motion plot for a surface impulsive source in Plexiglas. The cross indicates the beginning of the particle motion plot.

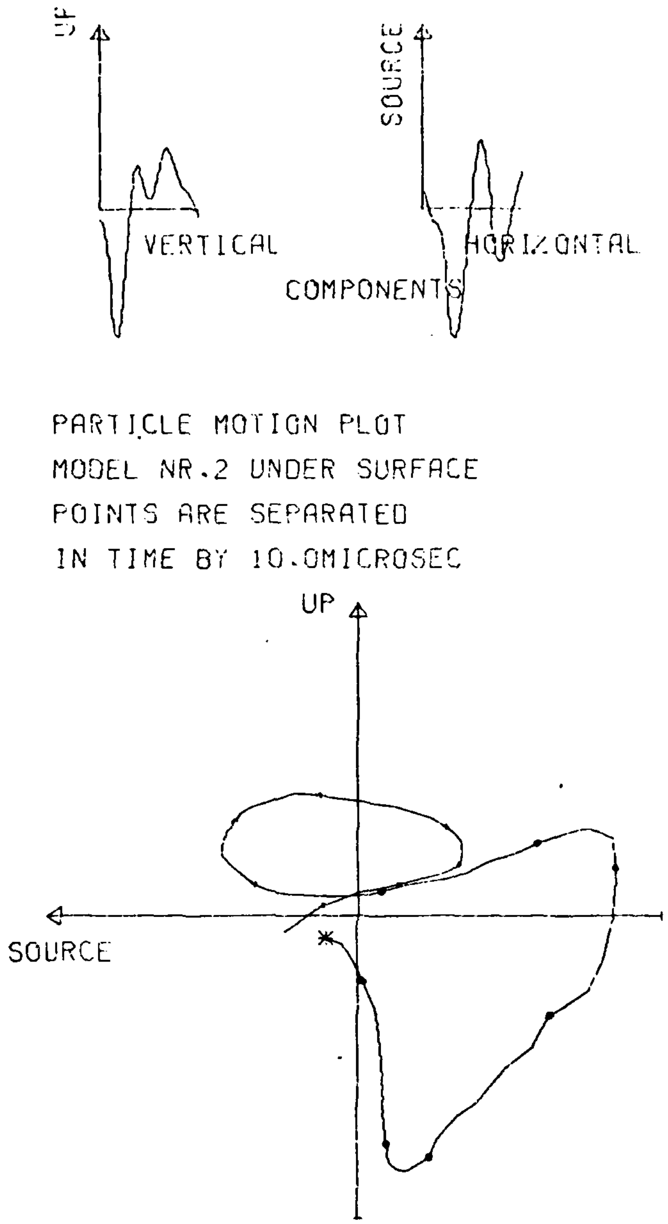


Fig. 14 Rayleigh wave signals (top) and particle motion plot for an impulsive "buried" source. The cross indicates the beginning of the particle motion plot.

PART II

INSTRUMENT RESPONSE OF THE KONGSBERG VLP-SYSTEM

EIVIND RYGG

ABSTRACT

The phase response curves for the vertical components of the VLP station at Kongsberg have been computed using the WWSSN phase response as reference.

INSTRUMENT RESPONSE
FOR THE
KONGSBERG VLP-SYSTEM

The phase delay response of the VLP(Very Long Period)-System at Kongsberg has not been available up to this moment. This information is necessary when using the VLP-data for studying problems like dispersion, focal mechanism, etc., and we have computed the instrumental phase shift curves by comparing the recordings with the WWSN data at the same location.

The VLP-instruments at Kongsberg are located in an abandoned silver mine displaced horizontally only 70 m. from the WWSS-instruments, which have been in operation since 1962.

From the VLP-instruments - kept in sealed tanks - the seismic signals are passed through different filters with different amplification, thus giving 3 components of High-gain recordings (ZHI,EHI,NHI) and 3 components of Low-gain recordings (ZLO,ELO,NLO).(In addition there is a displacement transducer giving displacement information sampled every 5. sec.)

The vertical VLP amplitude magnification curves are given in fig. 8. The purpose of this work was to calculate the corresponding phase response curves.

Events were selected which gave good fundamental mode Rayleigh wave recordings at WWZ and ZLO or at ZLO and ZHI simultaneously. Since only one of them - the ZHI component - is recorded on digital tape, we have digitized the paper seismograms for all three components. The sampling interval was 1 sec. The time resolution of the paper seismograms is poor. 1 mm = 4 sec. This means that for instance an error of 1 mm in the start point will result in a 90^{o} error in the phase delay curve at a period of 16 sec. For this reason the seismograms were photographically enlargened approx. 3 times prior to digitization.

The phase delay curves between the components were calculated by taking the Fourier transform of a weighted version of the crosscorrelation functions. In fig. 1 we show a sample crosscorrelation function which has been used to calculate the phase difference between ZHI and ZLO. Note that the form is very similar to that of an autocorrelation function, indicating nearly linear phase difference (mainly pure time delay).

Individual phase delay curves, average curves and smoothed average curves with standard deviation are given in figures 2 through 6.

We were not able to find events which gave acceptable signal to noise ratios at WWZ and at the same time gave recordings at ZHI that could be used. The net phase difference between ZHI and WWZ were therefore found by combining their relative delays to ZLO.

Finally, the phase response curves of ZHI and ZLO were adjusted for the calculated phase response of the WWSS network, T_S=15, T_g=100 (Anonymous 1966) and all three curves plotted versus period and versus frequency are given in Fig. 7.

As demonstrated in Figs. 2 and 5 the individual phase delay curves vary from event to event although the main trend is the same. This is especially pronounced between ZLO and WWZ. (The large phase fluctuations at frequencies larger than about 0.09 Hz in Fig. 2, are not significant since energy at higher frequencies is effectively damped by the High-gain filtering, see fig. 8.) There are two main reasons that the phase curves are dispersed:

1. Inaccurate start times, introducing linear phase shift superposed on the real phase angles. As mentioned above this error has been reduced by increasing the time resolution prior to digitazition.

2. Uncorrelated noise on the recordings. This is expected mainly to affect the correlations between WWZ and ZLO, since the instruments are different and on different locations, and inspection of Figs.2 and 5 shows that this is the case.
   By using a sufficient number of good recordings and taking the average such errors will cancel out.

The phase response curves given in this report cover the period Sept. 1971 - 24 March 1975. At that time the phototube amplifiers were replaced by solid state amplifiers and new response curves will be calculated for the period after 2 April 1975.

Also, response curves for the horizontal components before and after 2 April 1975 will be prepared.

References

Anonymous (1966):
World-Wide Standard Seismograph Network Handbook,
University of Michigan, Ann Arbor, Michigan U.S.A.

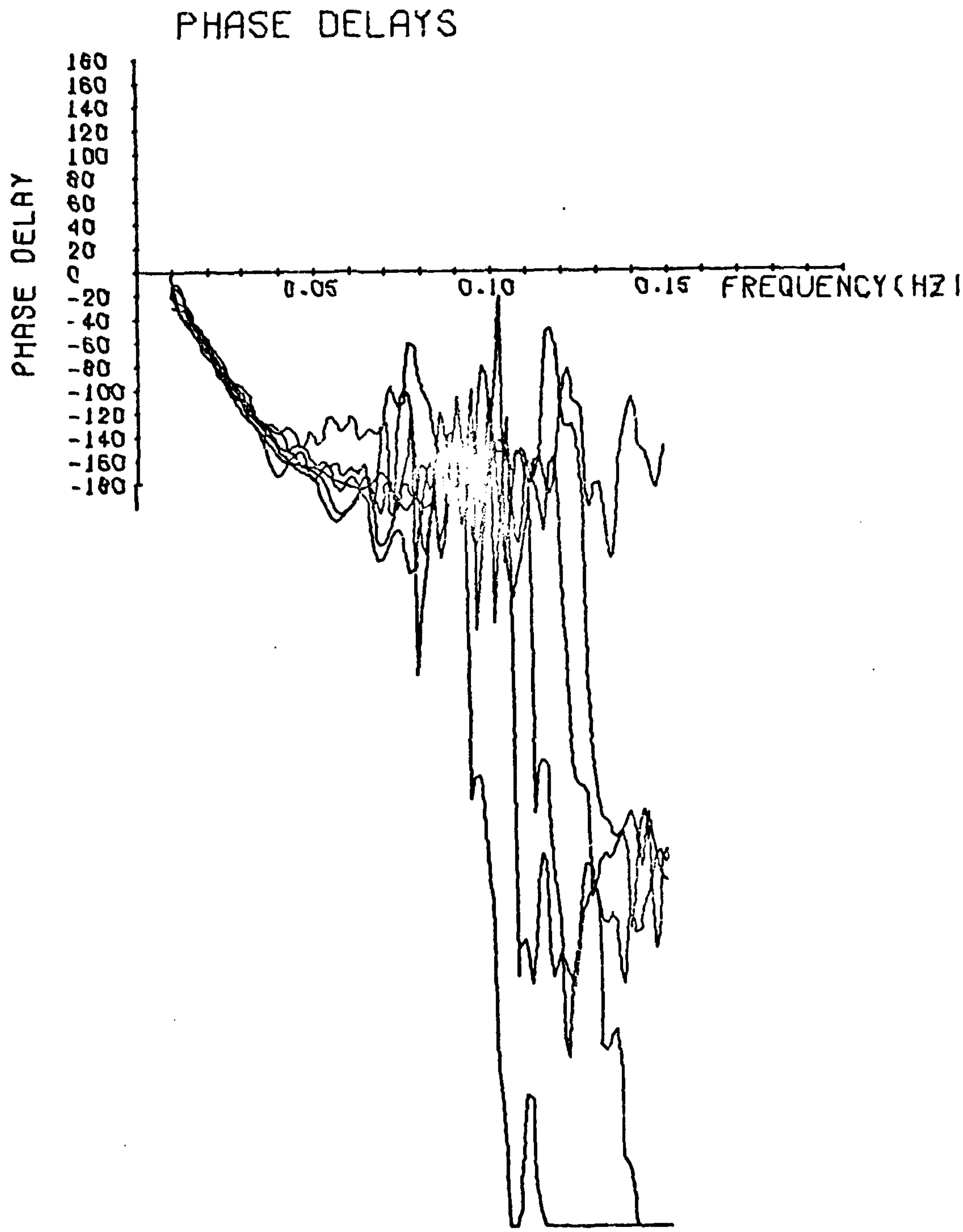


Fig. 2. Phase delay for ZLO relative to ZHI computed for 6 different events.

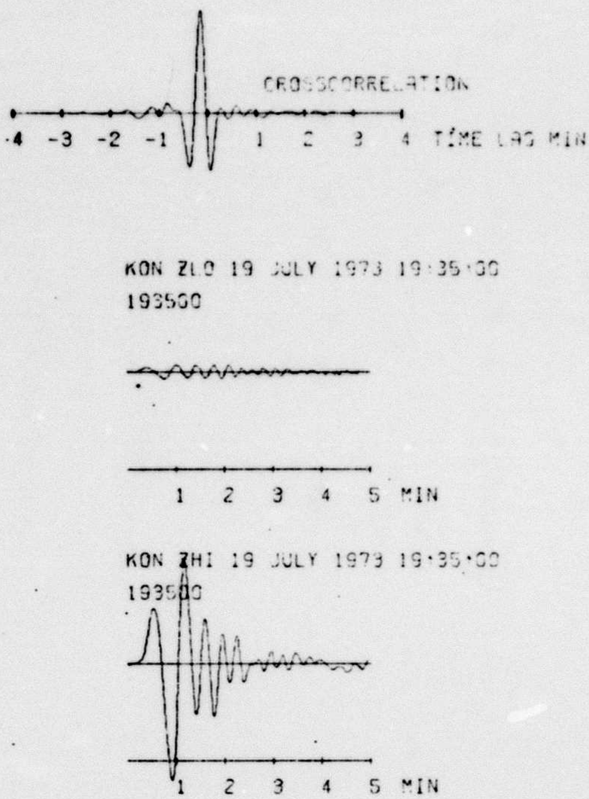


Fig. 1. Sample Crosscorrelation function used for calculating the phase difference between the Rayleigh Wave recordings at ZHI and ZLO.

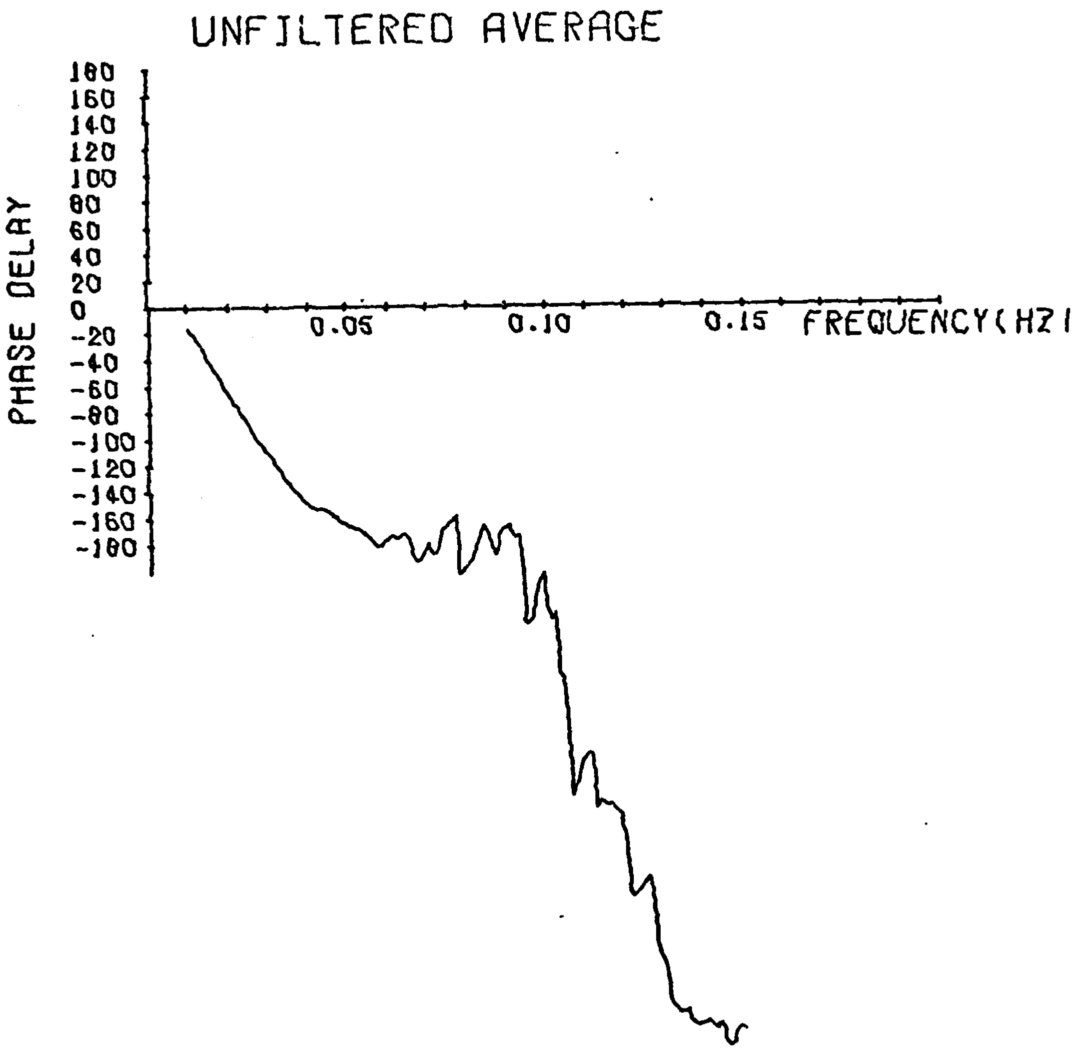


Fig. 3. Average phase delay of ZLO relative to ZHI computed for the curves in Fig. 2.

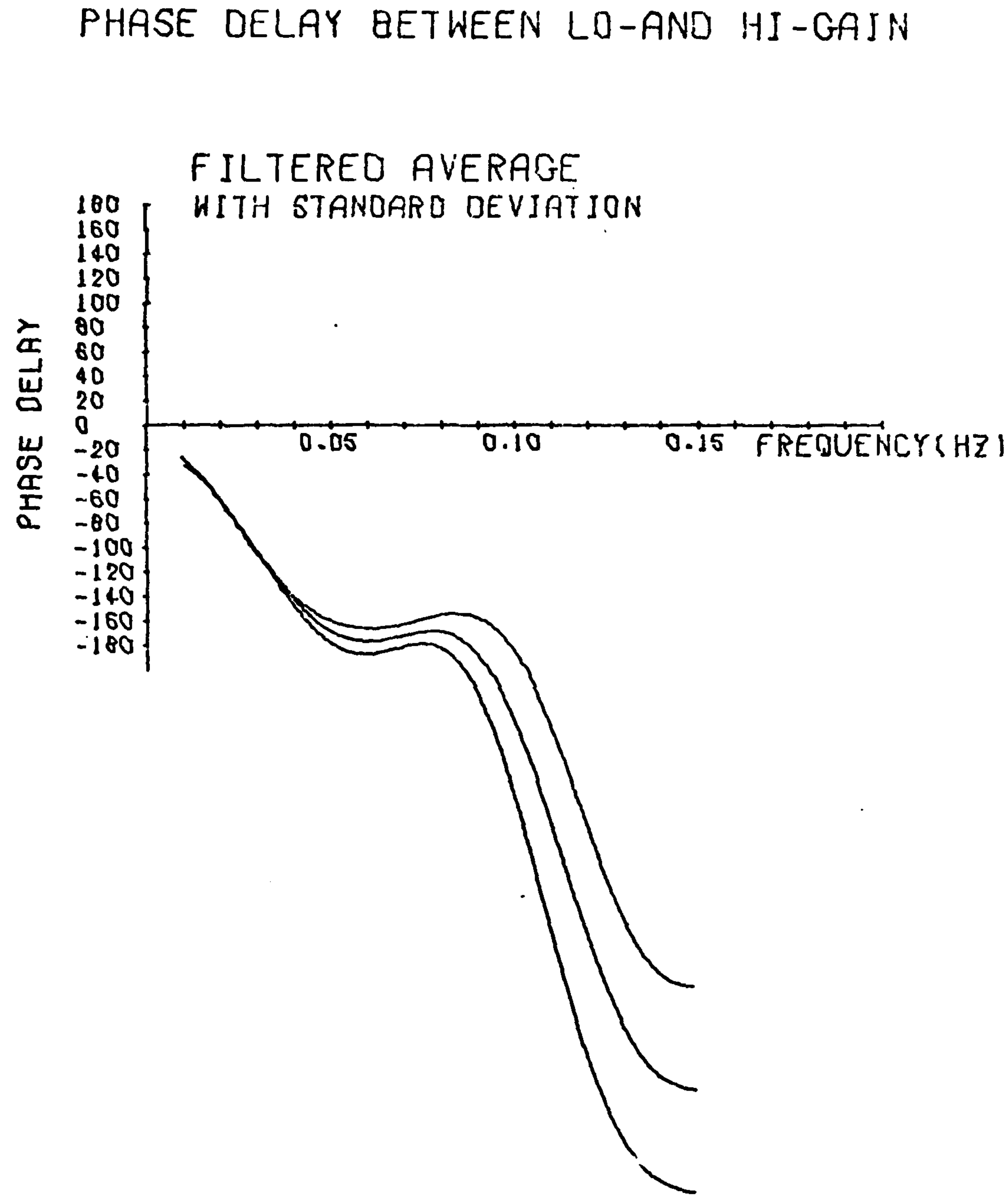


Fig. 4. A low pass filtered version of the phase difference curve in fig. 3 given with its standard deviation.

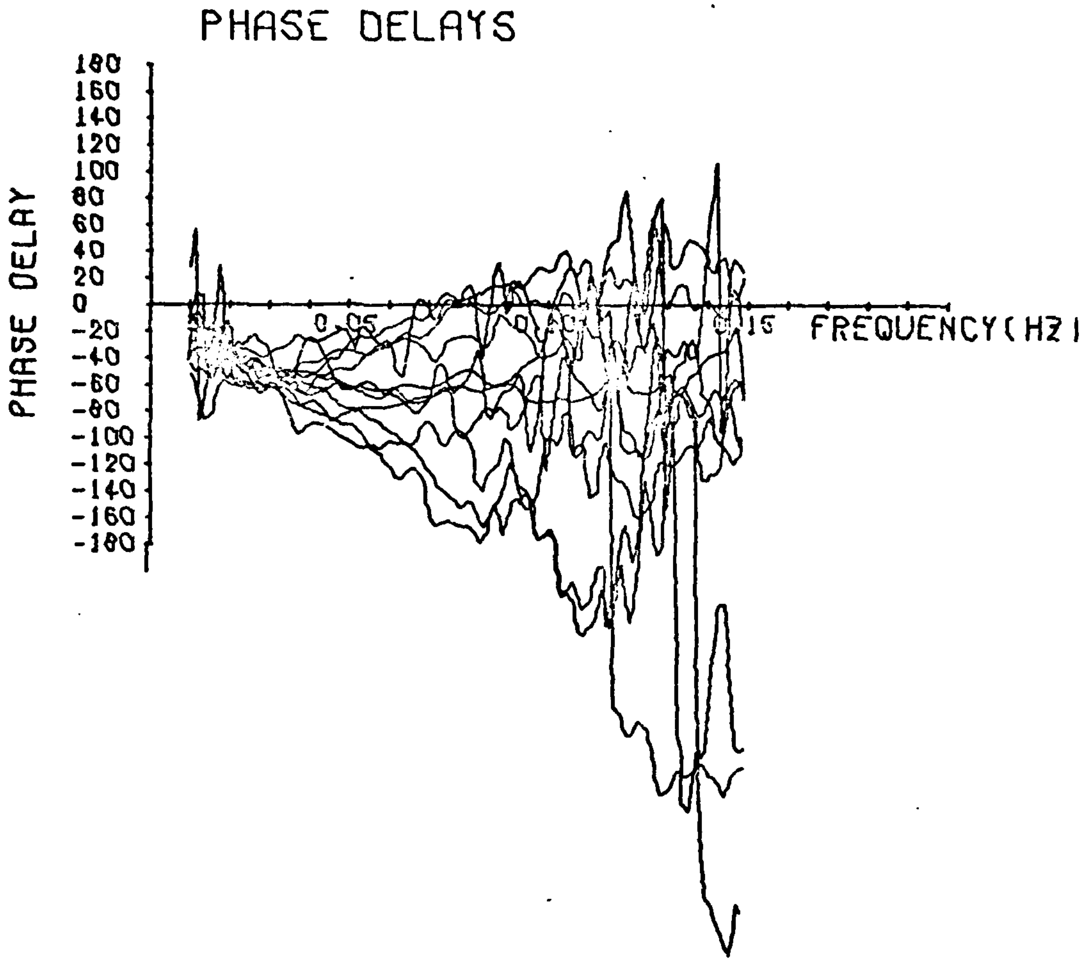


Fig. 5. Phase delay curves, WW relative to ZLO for 11 different events.

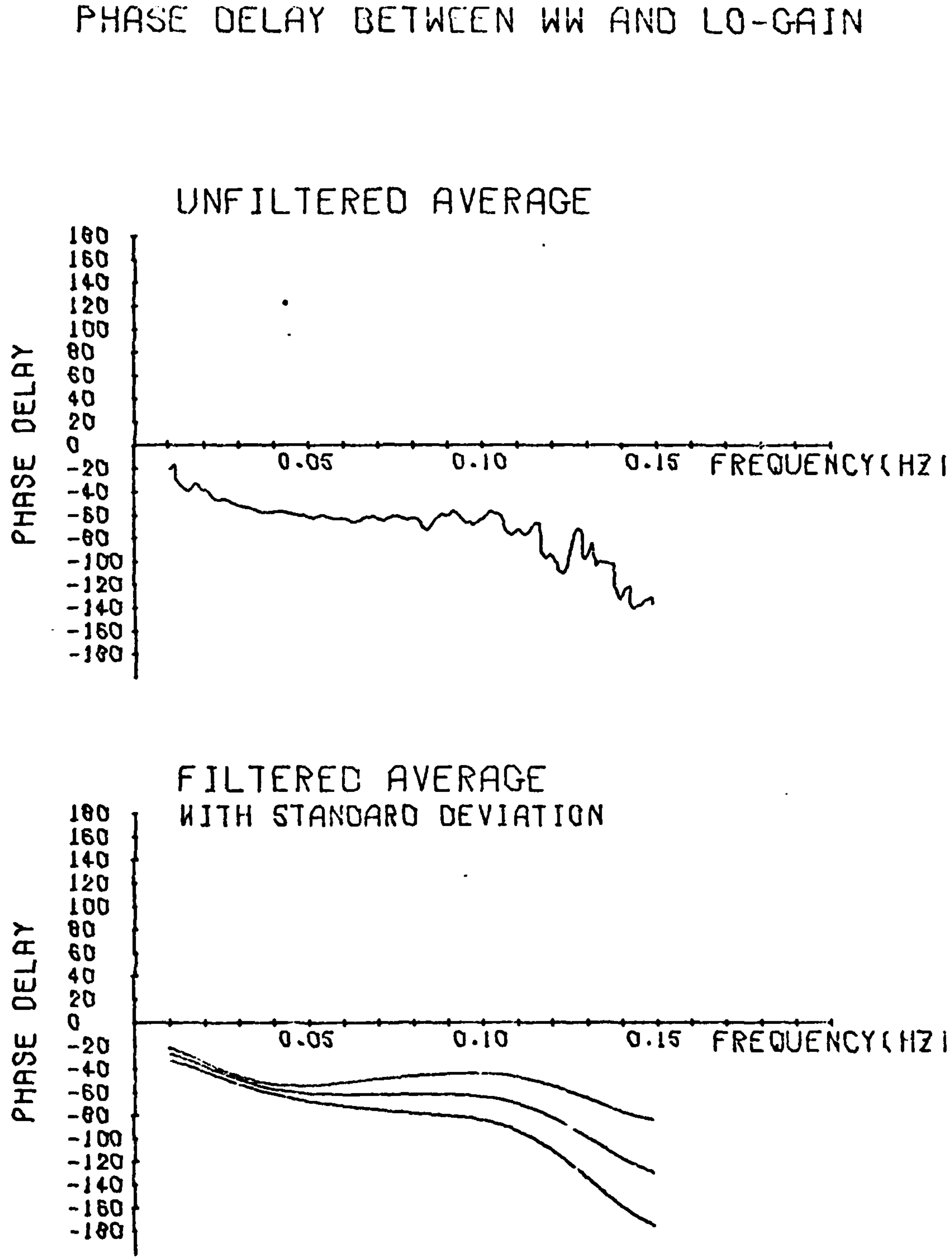
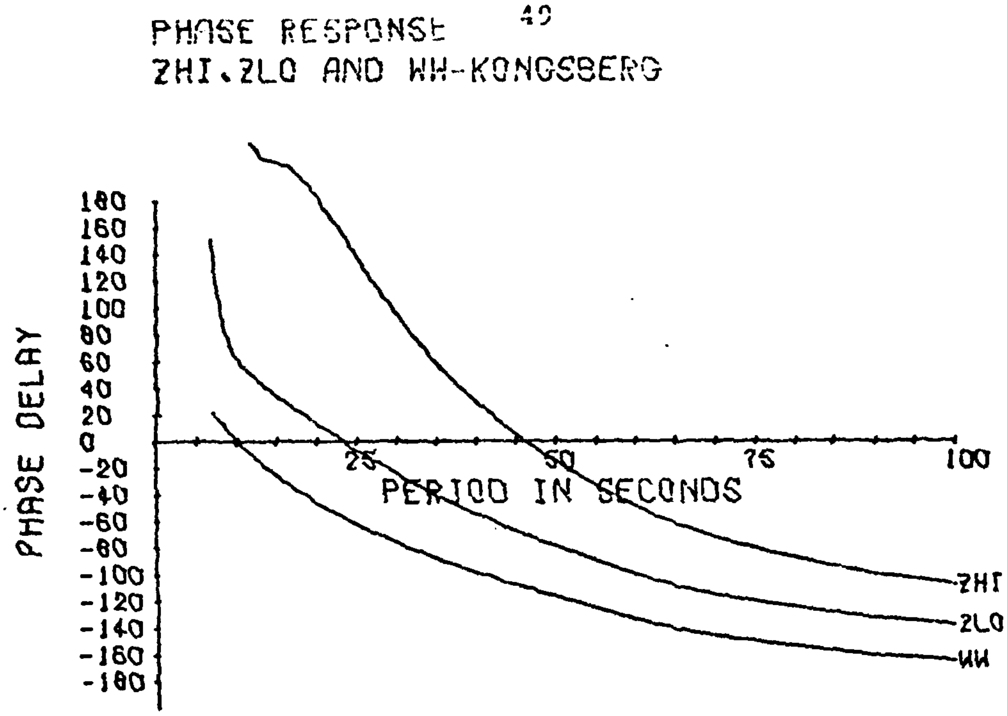


Fig. 6. Average and lowpass filtered average with standard deviation for the curves in fig. 5.



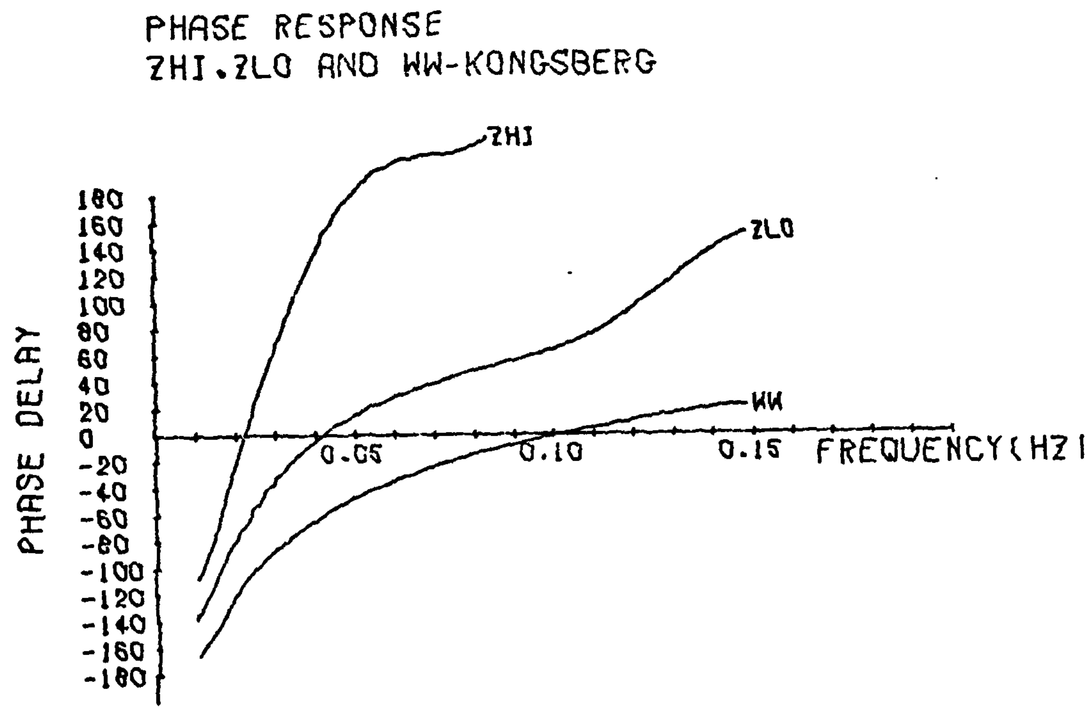


Fig. 7. Phase response curves versus period (top) and versus frequency (bottom) for *WW, ZLO* and *ZHI* Kongsberg, Norway.

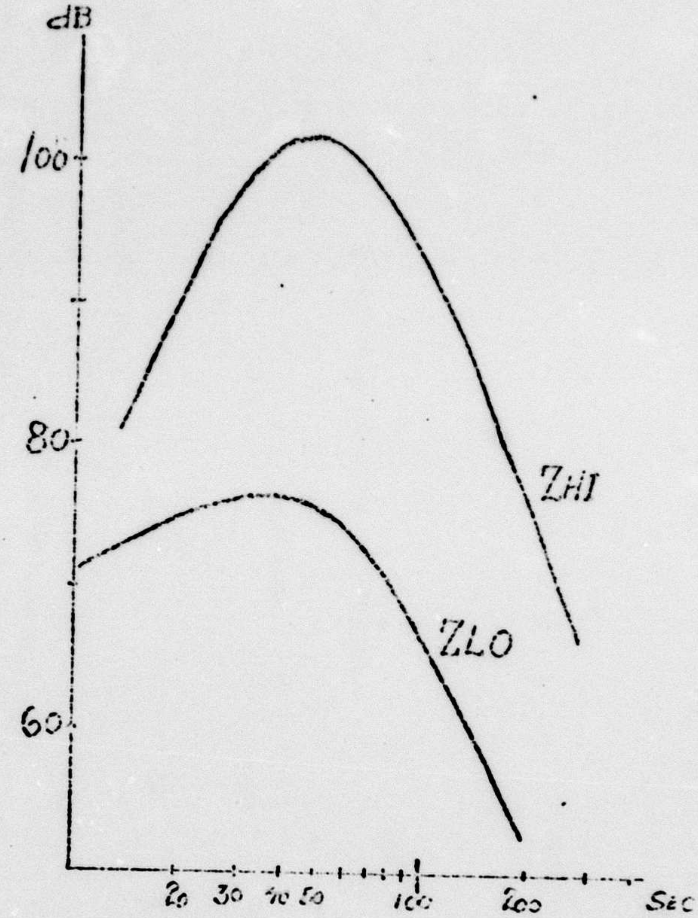


Fig. 8. Response curves for the two vertical components ZHI and ZLO of the Kongsberg broad band system.

PART III.

UNIDENTIFIED EVENTS RECORDED BY THE KONGSBERG VLP-SYSTEM

SVEIN VAAGE
and
EIVIND RYGG

ABSTRACT

Epicenter locations have been estimated for a number of unidentified events using the VLP-recordings of Kongsberg, Norway.

The epicenters grouped along the active seismic zones of the Mid Atlantic ridge. Events north of Iceland radiated very weak Love waves compared to the Rayleigh waves.

INTRODUCTION

At the VLP station in Kongsberg surface wave trains have been commonly observed without corresponding short period readings at NORSAR or the Norwegian station network (including Svalbard and Jan Mayen). Some of these events are not reported by the reporting agencies NOAA and ISC, and will be referred to as unidentified events in this paper.

Of particular interest are the small magnitude events with short but well dispersed wavetrains. The shape and length of the wave trains suggest mainly oceanic wave-paths (Fig. 1). Because of the broad band instrument response (see Fig. 8 in part II of this report) the VLP system is well suited for detecting these signals.

In this report the Kongsberg VLP recordings of 17 unidentified events from the time period Sept. 1972 - May 1974 have been used to roughly estimate the epicenter areas and to study the relative amounts of surface wave energy.

DATA AND DATA ANALYSES

Table I gives the recording times for the surface waves used in this study. The events listed in table I will hereafter be referred to by their numbers. Recordings of two typical events in the data base are shown in Figure 1.

TABLE I

No.	Day	Recording time	No.	Day	Recording time
1	9.Sept.72	13:02 - 13:07	9	2.Aug.73	13:05 - 13:14
2	21.Sept.72	08:58 - 09:06	10	15.Aug.73	13:34 - 03:39
3	31.Oct. 72	16:21 - 16[illegible]8	11	18.Aug.73	13:25 - 13:32
4	29.Jan. 73	17:38 - 17:44	12	28.Oct.73	10:18 - 10:24
5	10.Apr. 73	10:00 - 10:09	13	28.Oct.73	11:20 - 11:27
6	26.May 73	07:10 - 07:16	14	29.Oct.73	02:20 - 02:26
7	27.May 73	21:35 - 21:40	15	29.Oct.73	02:26 - 02:31
8	5.June 73	23:55 - 00:01	16	19.Dec.73	03:27 - 03:32
			17	18.May 74	23:45 - 23:52

The events are characterized by anomalously weak excitation of short period energy compared to the long period surface wave energy. Some of the events also (in the direction of Kongsberg) excite predominantly Rayleigh waves.
This can be an indication of the source mechanism (dip slip or strike slip type) but also the orientation of the fault relative to the recording station is of importance. These problems can of course not be properly dealt with when using recordings only from one station and without knowing the epicenter locations, but we have used the VLP-recordings to estimate the directions of approach and the great circle distances traversed by the surface waves. The individual locations thus found may be in error by several degrees, but by using a sufficiently large number of good recordings we get the average distribution of epicenters and can determine which seismic areas the unidentified events are concentrated in.

Estimation of the direction of approach of the surface waves.

The horizontal components were rotated in steps of $\pi/18$, and in the final runs $\pi/90$ to get the radial and transversal movements. We have used the following criteria when determining the correct angle of rotation:

At the correct azimuth the following requirements should be met:

1. Clearly separated and correctly dispersed wave trains on the radial and transverse components (Fig.2).

2. The absence of Love waves on the radial component and the absence of Rayleigh waves on the transverse component (Fig.2).

3. The phase difference between the radial and vertical components should be $\pi/2$ throughout the frequency band (Fig.3).

4. The crosscorrelation function between the radial and vertical component will be an odd function. Its value will be zero at zero lag (Fig.4). (Appendix A).

5. The energy distribution with time of the radial and the vertical component will be identical (Fig. 5).

Normally, all these requirements will not be met simoultaneously; one or more of the criteria are likely to fail even in cases when the remainders work quite well. The difficulties encountered by using the criteria listed above are mainly:

1. Poorly developed Love waves. This makes the interpretation of horizontal components very uncertain.

2. At short epicentral distances the arrival time difference between Love and Rayleigh waves is small, and combined with 1. this makes it difficult to discriminate on direction of approach.

3. Noise.

By testing the criteria 1-5 on a number of known events the azimuth error was within $\pm 8^{\circ}$ in the worst cases.

Estimation of the epicenter distance

For small magnitude events with mainly fundamental mode energy there are essentially two parameters which are of importance to estimate the epicenter distance:

1: The duration of the signal due to dispersion. (To avoid the influence of magnitude and radiation pattern differences the time duration must be measured in an energy vs. time distribution plot). (Fig. 5).

2: The difference in arrival times between Love and Rayleigh waves.

These two criteria can be simoultaneously evaluated from an energy vs. time plot (Fig.5). The energy density within a linearly tapered moving window was computed for different periods. The resulting energy curves were normalized relative to the maximum energy for each period and plotted as a function of period and time.

From the energy vs. time plots like the one shown in Figure 5 the time difference between the Love and Rayleigh waves and the time differences between Rayleigh waves of different periods have been read.:
The procedure was applied to a number (33) of events with known epicenters and origin times.

The resulting average time difference between the Love waves and the Rayleigh waves have been plotted as a function of Δ and azimuth on Figure 6. Since the dispersion curves of Love and Rayleigh waves in the period range of interest (20 - 80 sec) turned out to be nearly parallell, we have used average time differences between the Love and the Rayleigh waves. This means that for each period, 20, 25, 80 sec the arrival time difference between the Love wave energy maximum and the Rayleigh wave energy maximum was read (Fig. 5) and the average value was plotted in Figure 6.

The signal lengths (here defined as the time difference between Rayleigh wave periods of 40 sec and 20 sec) were also read from the energy diagrams (Fig.5) and plotted in Figure 6.

The great circle paths from the known events to Kongsberg covered an azimuth range of 120° (measured from North through West), and Δ varied between 12 - 38°. The epicenter locations found for these events when using the procedures outlined above turned out to be within $\pm 3^{\circ}$ of the solutions given by NOAA. Table II and Figure 7 gives the epicenter locations which were found for the unidentified events when the same procedure was applied to these. Note that events no. 2, 5 and 9 are outside the frames of the map. For these events which were located on the ridge about 30°N the epicenter distance errors may be much larger than $\pm 3^{\circ}$.

Not unexpectedly the epicenters in Figure 7 group along the active seismic zones of the Mid-Atlantic ridge. From these areas events with relatively little short period energy are commonly observed. A typical example was an earthquake swarm north of Iceland 27-29 Oct. 1973: Of 14 events clearly detected by the VLP system at Kongsberg, only two of the events were reported by the NORSAR short period detection system.

One objective of this study was to investigate the relative amount of Rayleigh wave energy compared to Love wave energy. As mentioned above the absence of Love waves results in uncertain azimuth and distance calculations. Two examples of events which radiated weak Love waves are shown in Figure 8. One event is known and belongs to the previously mentioned earthquake swarm of Oct 1973.

The other event belongs to the population of unknown events, and by the procedures described above it has been located north of Iceland. It should be added that all the events located north of Iceland radiated so weak Love waves that the transverse components could not be used and that Δ has been found by using only the signal length criterion.

TABLE II

Epicenter locations for the unidentified events determined from the surface wave recordings.

Event Nr.	Az (Deg.)	Δ (Deg.)
1	2	15
2	102	45
3	64	22
4	0	15
5	117	45
6	13	14
7	90	25
8	78	24
9	110	45
10	12	15
11	90	26
12	42	15
13	42	15
14	47	13
15	49	15
16	45	14
17	49	13

APPENDIX A

To see that the crosscorrelation function between the vertical and the radial component approximately becomes an odd function, let us define:

$v(t)$ = Vertical component (normalized)

$r(t)$ = Radial " "

$H(t)$ = 90^{o} phase shift filter (when used as a convolution operator = Hilbert transformation).

$v_{-1}(t)$ = Time reverse of $v(t)$

$C(\tau)$ = Crosscorrelation function between $v(t)$ and $r(t)$

$R(\tau)$ = Autocorrelation function of $v(t)$

Because of the 90^{o} phase shift between the components we can write:

$r(t) = v(t) * H(t)$

$C(\tau) = v(t) * v_{-1}(t) * H(t) = R(\tau) * H(t)$

Since $R(\tau)$ is a symmetric function $C(\tau)$ becomes an odd function and $C(o) = o$.

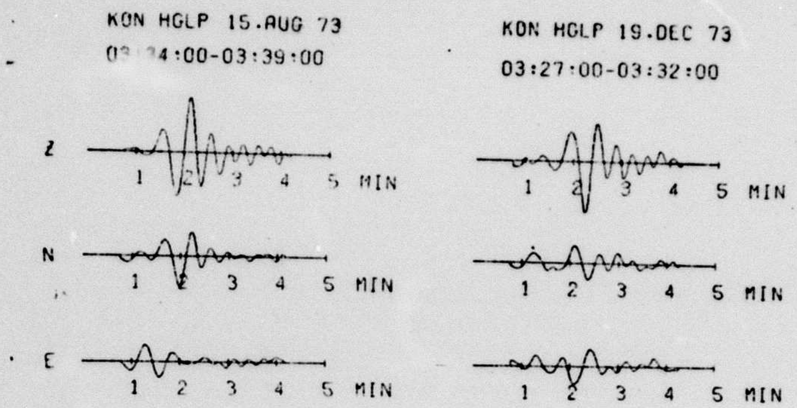


Fig. 1. Original recordings of event no. 10 (left) and event no. 16.

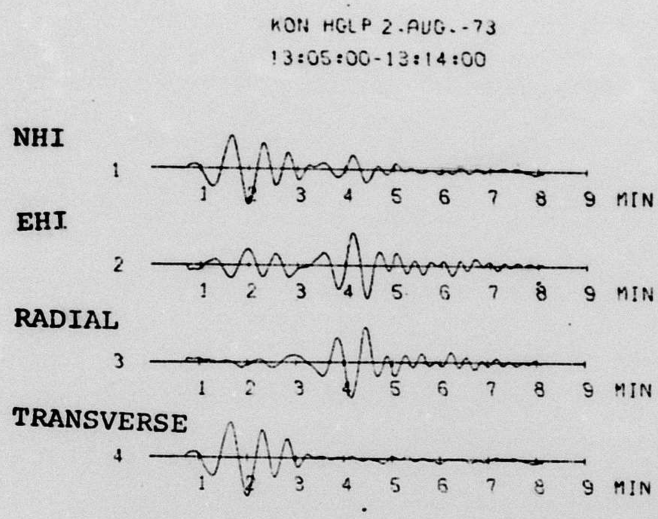


Fig. 2. Horizontal recordings of event no. 9 (top) Below: Radial and transverse components after a rotation of 110° (North through West).

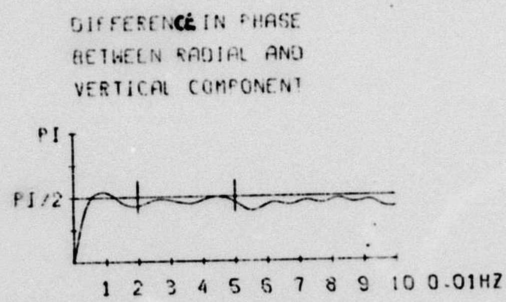


Fig. 3. Phase difference between the radial and vertical components of event no. 10 after a rotation of 12°.

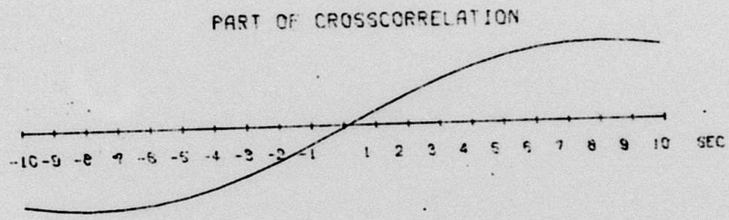


Fig. 4. Central part of the crosscorrelation function between the radial and vertical components of event no. 15.

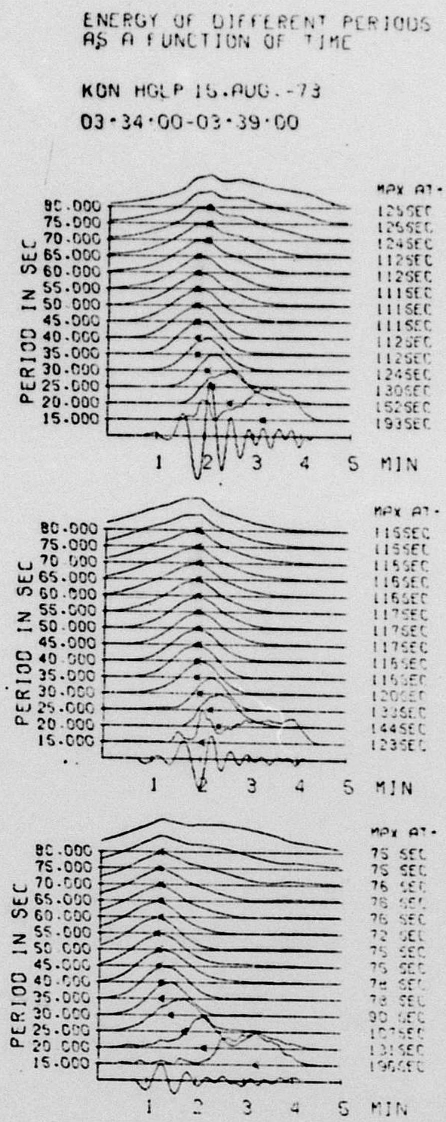


Fig. 5. Energy of different periods as a function of time, event no. 10. Top to bottom: Vertical, radial and transverse components. The stars represent the energy maximum for each period.

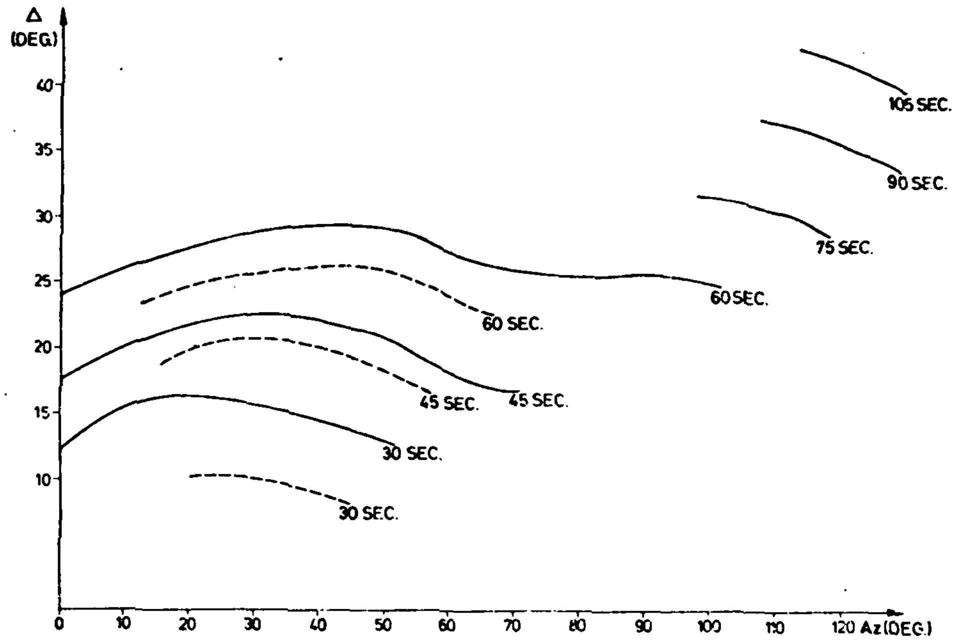


Fig. 6. Solid lines: Travel time difference between Love and Rayleigh waves at Kongsberg. Average for the periods (20, 25 ... 80) sec. Dotted lines: Travel time difference between Rayleigh waves of periods 20 and 40 sec.

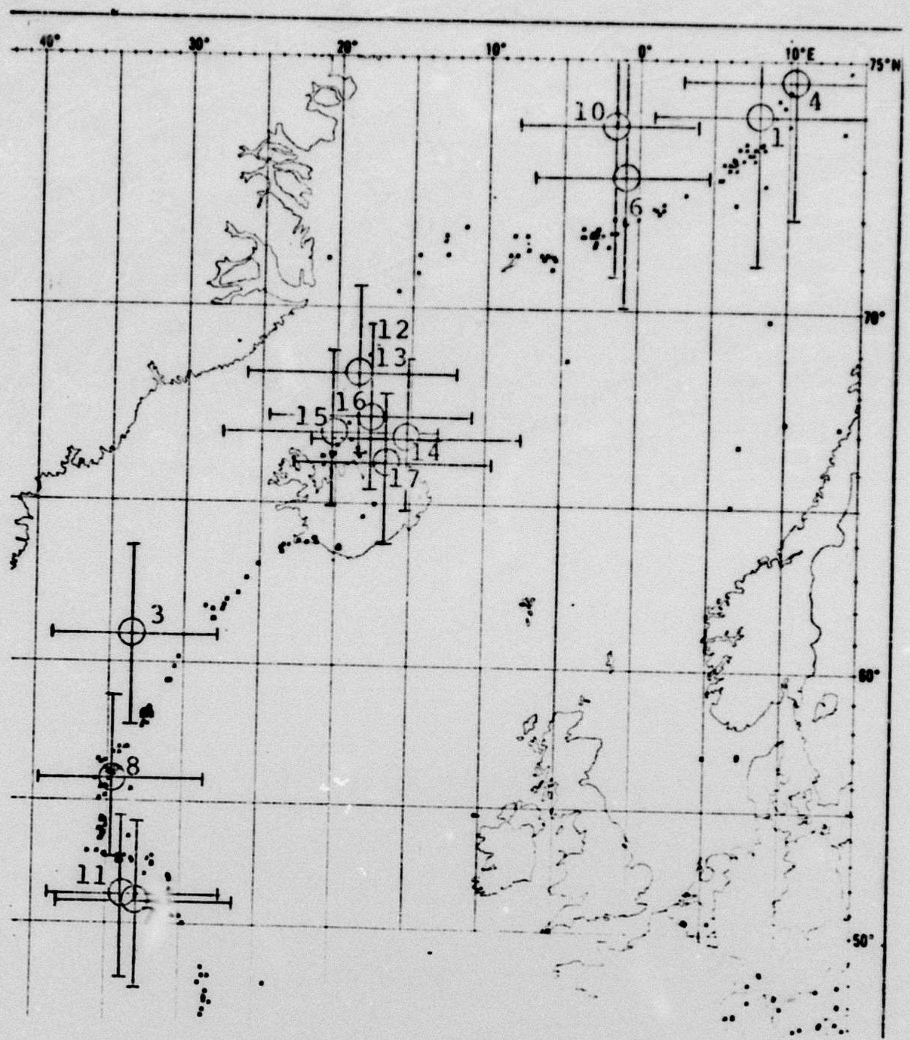


Fig. 7. Map of the seismicity in the Northern Atlantic, with estimated locations of the epicenters of the unidentified events (open circles). The horizontal and vertical bars indicate the approximate uncertainties in the epicenter locations.

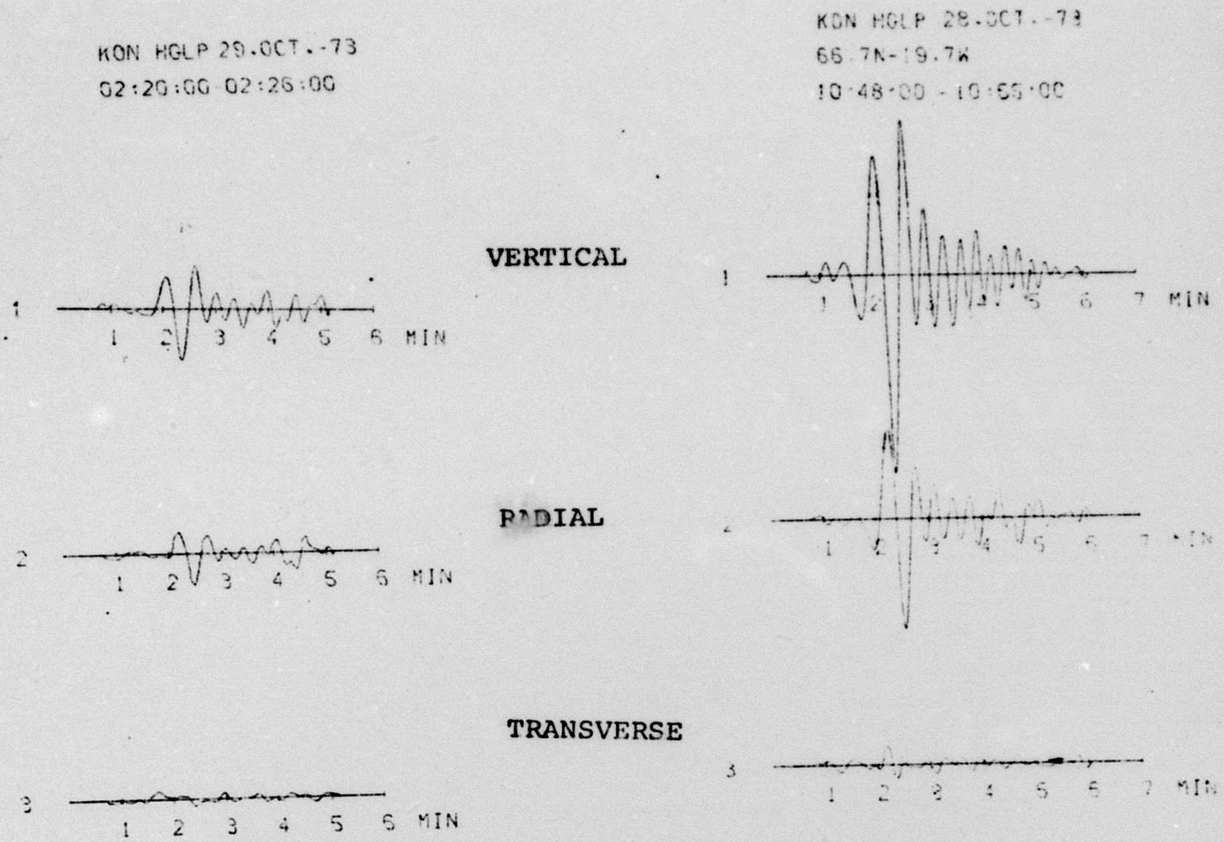


Fig. 8. Examples of events with weak Love wave radiation. Event no. 14 (left) and known event (right). Both epicenters were located north of Iceland.